Chemical vegetation management in *Pinus radiata* plantations in South Africa

by

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Declaration

I the undersigned hereby declare that the work contained in this thesis project is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

Summary

Pinus radiata is the most important timber tree planted in the western, southern and eastern Cape of South Africa, covering approximately 60000 hectares. The natural vegetation in these areas is mainly macchia, but exotic invaders like the *Acacia* and *Hakea* spp. cause severe problems. Macchia vegetation cannot be controlled successfully by means of slashing, hoeing or burning, because it resprouts rapidly in response to these treatments. Weed control in *P. radiata* plantations is mainly performed manually.

In this study the objective was to search for an alternative, more effective, cheaper, vegetation management option to manual weeding. Trials were conducted where a number of herbicides (acetochlor, glyphosate, hexazinone, imasapir, metsulfuron-methyl, tetrapion and thiazopyr) were tested under different vegetation management treatments. These included the effect of seasons on herbicide efficacy. Pre-emergent herbicides were added to knockdown herbicides to test if longer relief from weeds could be obtained. Different application methods were also tested. Intra-row weeding was compared to total chemical weeding.

Glyphosate at 1500g active ingredient per hectare (a.i./ha) and hexazinone at 2000g a.i./ha produced the best results for total weed control. In the southern Cape, weed control in summer was significantly better than weed control in any other season. No significant difference existed between intra-row weeding and total weeding. Chemical vegetation management was less expensive and more efficient than manual weed control.

Opsomming

Pinus radiata is die belangrikste aangelante boomspesie in die westelike, suidelike en oostelike dele van Kaapland en beslaan ongeveer 60000 hektaar. Die natuurlike plantegroei in hierdie gebiede is Fynbos, maar uitheemse indringers soos die *Acacia* en *Hakea* spp. kom ook volop hier voor. Fynbos spesies kan nie met behulp van vuur- of skoffelpraktyke beheer word nie, aangesien hierdie plante herspruit nadat dit gebrand of geskoffel is. Tradisioneel was onkruide met behulp van handearbeid beheer (skoffel en afkap).

In hierdie studie was gepoog om 'n meer effektiewe en goedkoper onkruidbeheermetode te vind as bogenoemde handearbeidmetodes. 'n Reeks eksperimente was uitgevoer met geselekteerde onkruiddoders (acetochlor, glifosaat, hexazinone, imasapir, metsulfuron-methyl, tetrapion en thiazopyr) onder verskillende onkruidbeheerpraktyke. Onkruidbeheerpraktyke het ingesluit die invloed van seisoene op onkruiddodereffektiwiteit, verskillende toedieningsmetodes en onkruiddodermengsels. Intrary bespuiting was vergelyk met totale area bespuiting.

Glifosaat teen 1500g aktiewe bestandeel per hektaar (a.b./ha) en hexazinone teen 2000g a.b./ha het die beste resultate gelewer vir totale onkruidbeheer. In die Suidkaap was onkruidbeheer in die somer beduidend beter as toediening in enige ander seisoen. Geen beduidende verskille het ontstaan tussen interry- en totale area beheer nie. Chemiese onkruidbeheer was goedkoper en meer effektief as hanbeheermetodes.

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Contents

1. Vegetation management in *Pinus radiata*: A literature review

1.1 Introduction

Weed control must have been one of the first cultural practices of early people as they realized that weeds interfered with food producing plants (Dangerfield and Merck, 1988). The practice of forest vegetation management has existed for close to forty years (Radosevich and Knowe, 1992). Vegetation management developed from weed control, where the emphasis shifted from killing weeds to managing the tree/weed environment (McAlonan, 1993). Forest vegetation management includes a wide selection of issues like, conservation, biodeversity, interactions, interactive dependence of fauna and flora, parasitism and allelopathy (Nambiar and Sands, 1993; Richardson, 1992). On a global scale, where plantation forestry is practised, forest vegetation management is also practised (Zedaker and Glover, 1993). The most common mechanism of managing vegetation is through the use of herbicides (Campbell, 1990; Zedaker and Glover, 1993). Vegetation management increases timber yield by eliminating competition (Clason, 1995; Frochot *et al.*, 1995; Richardson and West, 1993; Schumann, 1992) to supply the increasing world demand for timber (Dyck, 1995). Vegetation management research is not commonly published, because companies compete to produce wood more cheaply (Donald, 1986; Perrett, 1993; Zedaker and Glover, 1993).

This paper mainly reviews vegetation management in *Pinus radiata* plantations in South Africa, Australia and New Zealand. *P. radiata* is the most commonly planted tree species in the southern, western and eastern Cape of South Africa. These trees are grown mainly to supply the saw timber industry in the Cape (Department of Water Affairs and Forestry, 1993; Donald, 1986). Herbaceous weed control has become more important in the last decade than previously. Judged by increased research efforts, herbaceous weed control will become even more important in future (Teeter *et al.*, 1993; Turvey, 1984).

The main motivation for vegetation management in forestry is to prevent decreases in survival and growth of trees, through competition for limited site resources. Thereby stand access for silvicultural and harvesting operations is improved, fire risk is lessened by removal of forest fuel (Goodall *et al.*, 1989; Haigh, 1987) and tree growth and harvest schedules are accelerated, resulting in greater productivity (Beneke, 1980; Nambiar and Sands, 1993; Nelson *et al.*, 1981; Squire *et al.*, 1987;

Teeter *et al.*, 1993). Forest vegetation management can be defined as the discipline of channeling limited environmental resources away from weed species to the trees, especially until canopy closure (Nambiar and Sands, 1993; Walstad and Gjerstad, 1984 ex Richardson, 1992). Noland *et al.* (1995) found reductions in diameter increment, seedling biomass, stomatal density and the number of needle primordia caused by interfering vegetation on *P. banksiana*, *P. strobus* and *Picea mariana*.

1.2 Competition

1.2.1 Methods of measuring competition

Competition consists of a plant depleting a resource and another plant being limited by that same resource (Goldberg, 1995). The following plant physiological components can be measured: net photosynthesis, transpiration, stomatal conductance, xylem pressure potential and sap flow (Elliott and Vose, 1992; Loustau *et al.*, 1992). Physical environmental factors affecting competition include soil water, photosynthetic active radiation (PAR), air temperature and relative humidity (Elliott and Vose, 1992). Foliar nutrient content, especially nitrogen, phosphate and potassium can be measured (Elliott and Vose, 1992; Lin *et al.*, 1992). Root production, root collar diameter, needle length, tree height and groundline diameter are also commonly sampled to determine the effect of competition on tree growth (Caldwell *et al.*, 1995; Lin *et al.*, 1992; Oates *et al.*, 1992).

No formalised procedure exists to assess levels of competition. Competition assessment is usually subjective and in most cases relies on experienced forest managers, who know the weeds and their ecology (Richardson, 1992). Experiments designed to quantify competition usually consists of one of the following types: additive design, addition series, replacement series (substitutive), systematic, interference design (duration of removal design), plant halo design or neighbourhood design (Cousens, 1995; Radosevich and Knowe 1992; Rejmanek *et al.*, 1989).

1.2.2 Weeds in Pinus radiata plantations

It would be ambiguous to list all the important weeds in *Pinus radiata* plantations in South Africa, Australia and New Zealand. However, an attempt will be made to list the most important weed species, as well as potentially invasive weeds. Most major forest weed species are colonising plants that initiate succession after clearfelling of mature plantations (Turvey, 1984; Van Rossen and West, 1993).

Sclerophyllous scrub known as fynbos, is the natural vegetation where *P. radiata* plantations have been established in South Africa (Donald, 1986; Gous, 1995). Fynbos is floristically rich, (Donald, 1986; Goldblatt, 1978 ex Richardson *et al.*, 1989) normally containing the following families: Proteaceae, Ericaceae, Compositae, Leguminosae, Restionaceae, Cyperaceae, Thymelaeaceae, Bruniaceae and Iridaceae (Donald, 1986). Some individual indigenous species that frequently invade *P. radiata* plantations are; *Pteridium aquilinium*, *Gleichenia polypodiodes*, *Chrysanthemoides monolifera*, *Helichrysum* spp., and *Metalasia* spp. (Donald and Kirby-Smith, 1982; Donald, 1986; Gous *et al.*, 1992; Morze, 1979).

Exotic invaders commonly found in *Pinus radiata* plantations in South Africa are; *Hypochoeris radicata*, *Hakea* spp., *Acacia* spp., *Rubus* spp. and *Eucalyptus* spp., (Donald, 1986; Taylor, 1975).

In Australia *Eucalyptus* and *Acacia* spp. invade *P. radiata* plantations (Butcher, 1980; Hall, 1993). *Hypochoeris radicata*, *Pteridium esculentum*, *Rubus* spp., *Lantana* spp. and *Holcus lanatus* are some of the main weed species. *Trifolium subterraneum*, *Rumex angiocarpus* and *Lolium subulatum* are less important weeds (Cellier *et al.*, 1985; Nambiar and Zed, 1980; Turvey, 1984).

In New Zealand, *Ulex europaeus*, *Cytisus scoparius*, Poaceae and *Pteridium esculentum* are the main weed species (Richardson, 1992; Thompson, 1993). *Buddleja davidii*, *Cortaderia selloana*, *C. jubata*, *Rubus* spp., *Eucalyptus* spp., *Leptospermum scoparium, L. ericoides* and *Pinus radiata* regeneration have emerged as prominent weed species since 1984 (Preest, 1985; Richardson, 1992; Zabkiewicz, 1992).

1.2.3 Relative competitiveness

Richardson (1992), reported that very little published work exists on relative competitiveness. Throughout the rotation of a plantation, crop trees are subjected to different types of competition as the species composition changes (Allen *et al.*, 1995). During the first two years of a *Pinus* plantation, most damage is done by grasses and broadleaf herbaceous weeds which promptly invade the plantation after harvesting (Caldwell *et al.*, 1995; Dangerfield and Merck, 1988; Ray *et al.*, 1989; Wagner *et al.*, 1995). Competition from these groups of weeds are normally not sustained for more than two to three years. This is possibly because trees can obtain access to deep soil water which is out of reach of the weeds (Sands and Nambiar, 1984). After three years the trees are normally above the weeds and they are able to compete better for growing space than the weeds (Dangerfield and Merck, 1988).

Pine growth losses caused by woody weeds are normally more severe and occurs later in the rotation (age ten to fifteen years) than growth losses caused by grasses or herbaceous weeds (Dangerfield and Merck, 1988; Richardson, 1992). The crown volume index of *P. taeda*, grown in Alabama U.S.A., was twice bigger under herbaceous competition than under woody competition. Similarly, pine root density was severely reduced, as pines compete poorly with hardwoods (Burch *et al.*, 1995).

1.2.4 Limiting resources

1.2.4.1 Light

Methods of determining competition for light include: measurement of light interception, light use efficiency by mixture components, shade illumination, $^{14}CO_2$, frequency distributions associated with one-sided competition and plant dividers above and below ground (Cannell, 1992).

Light is the energy source for photosynthesis, therefore its availability and utilization are important factors affecting tree growth. High rates of photosynthesis are probably essential for high growth rates (Beneke, 1980; Minogue *et al.*, 1991). Most pine species are shade intolerant, therefore they don't thrive and usually perish under low light intensities. *P. radiata* seedlings grown under overtopping vegetation assimilated less carbon dioxide and received close to 40% less photosynthetic active radiation (PAR), than unshaded seedlings (Beneke, 1980; Caldwell *et al.*, 1995; Minogue *et al.*, 1991). In the Southern U.S.A., *P. taeda* seedlings can only reach maximum photosynthesis under 100% sunlight, whereas woody weeds could reach maximum photosynthesis under 30% sunlight (Minogue *et al.*, 1991).

Pinus spp. have thick, bundled, round needles which disperse light, and shades one another. Hardwoods have broad leaves, perpendicularly orientated to the light direction, usually arranged so that mutual shading is reduced to a minimum. Vegetation management should therefore reduce shading of pine seedlings by competing vegetation, thereby improving pine photosynthesis, to ultimately increase pine productivity (Beneke, 1980; Minogue *et al.*, 1991). In the central North Island of New Zealand, shading by herbaceous weeds is normally temporary, as weed growth declines because of moisture and temperature restrictions in the hot, dry months (Richardson, 1992).

Interspecific light competition has beneficial effects. As canopy closure shades out light, the competing vegetation is suppressed and often eradicated. Thereafter, water and nutrient competition also declines. Usually, weeding is not necessary after canopy closure (Nambiar, 1989; Richardson, 1992). Therefore, vegetation management should be designed to accelerate initial tree growth (Gous, 1995). Poor early growth due to improper weed control and inadequate establishment practices (poor soil preparation, too wide espacement) will increase the time to canopy closure. This will cause a negative effect on the growth potential of a plantation (Richardson, 1992).

1.2.4.2 Water

Water stress in *P. radiata* cause a significant reduction in transpiration and a significant reduction in growth (Nambiar and Zed, 1980; Squire *et al.*, 1987). Stem, diameter and root growth are diminished by water shortage before transpiration and photosynthesis are affected (Rook *et al.*, 1977). Nambiar and Zed (1980) found on relatively dry sites that even a 5-10% weed cover could cause enough water stress to impair *P. radiata* growth. Various studies have shown that the removal of competing vegetation, especially on dry sites, will enhance tree growth (Caldwell *et al.*, 1995; Cellier and Stephens, 1980a; Nambiar, 1989; Nelson *et al.*, 1981; Richardson, 1989). Diverse weed species show different rooting properties and depths, therefore water usage patterns also vary (Flinn *et al.*, 1979). Competition for water by herbaceous weeds, with relatively shallow roots, diminished over a three year period following establishment, as *P. radiata* roots tapped water from greater depths (Richardson, 1992; Sands and Nambiar, 1984).

Plant moisture stress (pms) is a direct indication of the water supply from the soil and the demand for water from the plant. As the pms increases, physiological processes are reduced, thereby limiting productivity until the plant dies (Sands and Nambiar, 1984; Sands and Mulligan, 1990; Squire *et al.*, 1987). Therefore, pms is a good indicator of the water availability and growth potential of the plant (Cleary and Zaerr, 19??).

1.2.4.3 Nutrients

Nambiar (1989) stated the difficulty in distinguishing between competition for water and nutrients, because of its complex interactions. Stand volume of *P. taeda* grown in Florida increased nine times when fertilizer was applied, ten and a half times when vegetation was controlled and twenty one and a third times when weeding and fertilization were combined (Colbert *et al.*, 1990 ex Schumann, 1991). The above results indicate the interaction between fertilization and weed control. Fertilizing without vegetation control can result in increased weed growth, inducing moisture stress, resulting in tree growth reductions and even mortalities (Cellier and Stephens, 1980b; Flinn *et al.*, 1979). Therefore, fertilization should not be performed unless accompanied by weeding (Cellier and Stephens, 1980b; Nambiar, 1989; Schumann, 1991; White and Newton, 1990).

P. radiata, grown under weed competition, experienced a reduction in foliar nitrogen, phosphate and potassium (Sands and Nambiar, 1984). Pine growth in the southern U.S.A. is often limited by weed induced deficiencies in nitrogen and phosphorus (Minogue *et al.*, 1991; White and Newton, 1990). Weeds directly compete for nitrogen with *P. radiata*, thereby diminishing crop growth (Richardson, 1992). Clinton and Mead, (1990 ex Richardson, 1992) found that on a dry site (South Island of New Zealand) four year old *P. radiata* had to compete with weeds for water and nitrogen.

However, accompanied forest vegetation can contribute improvements to tree crops that outweigh the negative effects of competition (Richardson, 1992). See oversowing, paragraph 1.3.6.

1.3 Vegetation management methodology

Vegetation management should be integrated with establishment and silvicultural practices and not treated as a separate exercise (Balneaves, 1993; McAlonan, 1993; McAlonan, 1992 ex Richardson 1992). Effective chemical weeding is superior to manual weeding (Gous, 1995; Gous *et al.*, 1992) and covercropping (Schumann, 1991), when cost benefits and duration of control are considered. Care should always be taken of the toxicity of herbicides. Toxicity is expressed by the LD_{50} which is calculated as the dose of a chemical (mg/kg body weight) lethal to 50% of the test animals. Herbicides commonly used in *P. radiata* plantations for vegetation management are listed below.

1.3.1 Herbicides

Atrazine (LD_{50} = 5.100mg/kg) is used at high rates, 8000g active ingredient per hectare (a.i./ha), as a post-planting treatment to establish pines in New South Wales, Australia (Hall, 1993). Atrazine in granular formulation can safely be applied to *Eucalyptus nitens*, *E. saligna*, *E. botryoides* and *Cupressus macrocarpa*. In New Zealand a 90% atrazine granule, applied at 3.8g per tree, over *P. radiata* gave total weed control for twelve months (Davenhill *et al.*, 1995). Atrazine is not registered for forestry in South Africa.

Glyphosate (LD_{50} = 4.300mg/kg) is possibly the most successful herbicide ever produced with a very wide range of target weeds. Glyphosate is a non-selective systemic herbicide, with a wide range of target species. Directed sprays using 1.5 to 2% solution or 1500g a.i./ha controls macchia in *P. radiata* satisfactorily. Extreme care must be taken to avoid getting spray solution onto *Pinus* seedlings and young growing tips, as high mortality can occur (Goodall *et al.*, 1989; Gous, 1995; Minogue *et al.*, 1991). Zutter *et al.* (1988) however reported 2000g a.i./ha applied over-the-top to *P. taeda* caused no mortality and improved diameter at breast height (dbh) by 30% and height by 13%. Glyphosate is registered on a wide range of weeds for forestry in South Africa.

Hexazinone (LD_{50} = 1.690mg/kg) is a selective, systemic herbicide with residual effect. Registration includes over-the-top application to the trees. *Gleichenia polypodiodes* is successfully controlled by hexazinone at 2000g a.i./ha. In South Africa, unlike New Zealand and Australia, hexazinone causes no recorded damage to *P. radiata* (Gous, 1995; Gous *et al.*, 1992). The possible reason for this phenomenon is that environmental conditions differ between these countries (therefore, the trees are probably less susceptable to herbicide damage in S.A.). Hexazinone is available in a liquid and granular formulation. The granular formulation is activated by rainfall and assimilated by weed roots. No significant difference was found between efficacy of liquid and granular formulations of hexazinone (Gaskin and Zabkiewicz, 1986; Preest, 1986). Hexazinone is the only herbicide specifically registered for use in *P. radiata* plantations in South Africa.

Imazapyr controls a wide spectrum of herbaceous weeds in the southern U.S.A. (Minogue *et al.*, 1991). *P. taeda* is very tolerant to imazapyr at 800g a.i./ha to 2100g a.i./ha, due to limited foliar absorption, limited translocation through the root and needle endodermis and root exclusion (Cain, 1991; Minogue, 1990 ex Minogue, 1993). However, imazipyr at 250, 500 and 1000g a.i./ha had little effect on fynbos vegetation in the western Cape (Gous *et al.*, 1992). In South Africa imazapyr is registered as an *Eucalyptus* stump killer.

Metsulfuron-methyl (LD_{50} > 5.000mg/kg) is a sulfuron-urea herbicide. Its main use is for the eradication of *Rubus* spp. at 25g/100M water (Goodall *et al.*, 1989). Metsulfuron-methyl in a tank mixture with glyphosate is an effective pre-plant spray in New Zealand (Thompson, 1993). Metsulfuron-methyl applied at 15, 30 and 45g per hectare gave insufficient herbaceous weed control in *P. radiata* (Gous, 1995). Michael (1985) similarly found little effect on herbaceous weed control by metsulfuron-methyl at 140 and 280g a.i./ha. However, Goodall *et al.* (1989) claimed that metsulfuron-methyl was safe as an over-the-top application to *P. patula* saplings, for woody weed control. Metsulfuron-methyl is registered in South Africa as an *Eucalyptus* stump killer and for the eradication of *Rubus* spp.

Picloram (LD_{50} = 8.200mg/kg) mixed with diesel can be used for *Solanum mauritianum* and *Eucalyptus* basal treatment (Lyle, 1981).

Simazine and terbuthylazine both at 4400g /ha controls a broad spectrum of weeds and grasses with success (White and Newton, 1990). Neither simazine nor terbuthylazine is currently registered for forestry weed control in South Africa. However, trials for registration of both herbicides are underway.

Sulfometuron methyl (LD_{50} > 5.000mg/kg), is used extensively in the southern U.S.A. for herbaceous vegetation management (Busby, 1988). Sulfometuron methyl is not registered for forestry in South Africa.

Triclopyr (LD_{50} = 713mg/kg) is a selective herbicide that is absorbed by foliage and roots. Triclopyr when applied over-the-top to *P. radiata* at 288g a.i/ha caused no mortalities, but at 1800g a.i./ha reduced height and diameter growth, compared to a control (Balneaves, 1981; Balneaves and Davenhill, 1990). Triclopyr at 480g/ha (half the dosage required for woody weed control), caused severe mortality to *P. patula* seedlings (Goodall *et al.*, 1989). Triclopyr is suitable for woody weed control (Balneaves and Davenhill, 1990; Zedaker and Glover, 1993). Triclopyr is registered for forestry weed control in South Africa at a 2% solution in water as a foliage application, or at a 2% solution in diesel as a stump and basal stem treatment.

1.3.2 **Application methods**

i) Handheld applicators

Liquid herbicide applicators are classified by the volume of mixture applied per hectare. Lyle (1981) describes three categories, i.e. high volume sprayers (250M/ha and higher), low volume sprayers (normally motorized, 50-60M/ha) and ultra-low volume sprayers (less than 50M/ha). Granular herbicides are very new to South Africa. The application of granular herbicides are simple compared to liquid herbicides. Granular herbicides require no mixing (as they are applied without water) and no calibration (applicator delivers a measured quantity of product) of application equipment. Accurate, fast, quick, easy application is therefore possible (Stewart, 1993).

Spot herbicide release by handheld applicators is more economical and environmentally more acceptable than other application methods, because less area is treated and therefore less herbicide is used. Spot herbicide release costs depend on the number of stems per hectare. For 1500, 1000 and 600 stems/ha the cost is approximately 14%, 10% and 6% respectively of a total broadcast herbicide application. Trials in New Zealand with granular and liquid formulations of the same herbicide at equal a.i. rates showed no significant difference on diameter growth of *P. radiata*. Two spot applicators are available, i.e. a spot gun (liquid application) and the "Weed-a-metre" (granular application) (Davenhill *et al.*, 1995; Davenhill *et al.*, 1989; Richardson *et al.*, 1995; Zabkiewicz, 1989). "No-mix" (glyphosate in a mineral-oil carrier) can also be used for spot release. However, it was developed with its applicator, as an ultra-low (3M/ha) applied herbicide to treat large areas.

ii) Tractor drawn applicators

In the southern U.S.A. and Canada ground machinery is favoured to treat sensitive areas, where aerial application is not advisable. Application equipment may be mounted on farm tractors, skidders, four wheel drive off-road vehicles and trac-driven tractors. Three basic designs are found: spreaders, ground sprayers and mistblowers. Spreaders apply solid or granular herbicides, usually by rotating disk, or by air pressure driven blowers. Swath width varies from 1.5m to 28m. Ground sprayers apply water diluted herbicides normally through a boom and nozzles to the inter-row. Mistblowers apply water diluted herbicides, by releasing spray through nozzles in front of high speed fans, which blow the spray mist onto the target area. Mistblowers are not commonly used in forestry due to fine herbicide vapour and subsequent drift risk (Desrochers and Dunnigan, 1991; Minogue *et al.*, 1991; Richardson, 1992; Zedaker and Glover, 1993)

iii) Aerial applicators

This method of herbicide application is fast, economical and with very uniform application patterns. It is desirable especially over dense, restrictive vegetation, in remote areas, on steep slopes and where large areas are to be treated (Minogue *et al.*, 1991; Perrett, 1993; Turvey, 1984). Sixty seven percent of the herbicides applied in Canada in 1988, were done by aircraft (Campbell, 1990). Fixed-wing aircraft or helicopters may be used for application of liquid or granular herbicides. In the U.S.A. and New Zealand helicopters are preferred over fixed-wing aircraft because forestry areas are relatively remote, making "turn-around" time (taxi time to and from airstrips, to land refuel and refill with herbicides), long and expensive. However, in Australia, fixed-wing aircraft are more frequently used than helicopters (Boomsma, 1993; Turvey, 1984).

Helicopters have the following advantages over fixed-wing aircraft: They can land on site to refuel and fill-up with herbicide; they are more suited to treat small irregular shaped areas; they can fly slower causing less shearing of droplets, causing less drift; they follow contours better for even application and are more accurate over steep broken terrain (McDonald and Fiddler, 1989; Minogue *et al.*, 1991; Ray *et al.*, 1993).

In New Zealand, herbicide efficacy and productivity were improved, from 22ha/hr to 38ha/hr, by reducing aerial applied spray volume from 160M/ha to 80M/ha (Jones, 1995). Ray *et al.* (1993) concluded that a reduction in aerial spray volumes to 50M/ha, increased a.i. recovery and reduced application costs. Aerial herbicide application to *P. radiata* plantations in South Africa are very seldomly practised. The main reason presumably is that selective herbicides for over-the-top application has only recently (1995) been registered for pine release. Another reason is that no helicopters are in use in *P. radiata* areas and airstrips for fixed-wing aircraft are up to 200km away.

The United States Department of Agriculture, Forest Service developed a computer aerial spray model, known as the FSCBG (Forest Service Cramer-Barry-Grim) model. This model predicts the behaviour (deposition and dispersion) of spray material, through nozzles into the wake of the spray craft, as a function of atomization, weather and application parameters. FSCBG provides a tool to obtain off-target deposition data without conducting extensive and expensive field testing (Barry, 1985; Barry and Teske, 1993; Teske *et al.*, 1993).

1.3.3 Mechanical methods

Mechanical weed management cannot be practised where slopes are too steep, tree espacements are too small, or where soils are unstable and easily erodible. Physical obstructions such as large rocks, large stumps and debris from harvesting can severely hamper mechanical weeding. In New Zealand and Australia respectively, only 3% and 10% of the annual vegetation management is done mechanically (Boomsma and Hunter, 1990; Minogue *et al.*, 1991).

Tractor-mounted mowers, brush-cutters and chopper-rollers are the equipment most commonly used for mechanical weeding (Hall, 1993; Minogue *et al.*, 1991; Richardson, 1992). Care has to be taken that soil compaction by this equipment does not cause greater growth reductions than the benifits to tree growth by controlling the vegetation. In South Africa, mechanical vegetation management is seldom done in in *P. radiata* stands. One-way soil cultivation does not control weeds in the tree row (Minogue *et al.*, 1991).

Soil cultivation, as part of site preparation, improves the physical condition of the soil. These operations create a degree of mechanical vegetation management, as weeds are removed by ploughs, discs and rippers (Mason *et al.*, 1988 ex Richardson, 1992). Hand held brush-cutters can be used for mechanical weeding, but these machines pose a high risk to operator safety (Thomas *et al.*, 1988 ex Minogue *et al.*, 1991).

1.3.4 Manual

Labour costs normally dictate the extent of how much manual weeding can be afforded (Balneaves, 1981; Donald and Kirby-Smith, 1982). Hoeing, hand pulling and slashing were the most frequently used methods of vegetation management in *P. radiata* plantations in South Africa (Donald, 1986). However, the increase in labour costs in South Africa and the high labour costs in Australia and New Zealand have necessitated chemical weeding options to become more important since 1990 (Gous *et al.*, 1992). Therefore, spot release from weeds, by handheld applicators, are preferred above total area spray, because less labour is required than for total area sprays.

Balneaves (1981) reported that manual vegetation control in Australia and New Zealand is only used as a last refuge, because of its high costs. In South Africa, labour is less expensive than in the above two countries, but productivity is much lower than in Australia and New Zealand. However, manual release (1m diameter hoeing around the tree) from competing vegetation is still practised in *P. radiata* plantations in South Africa.

1.3.5 Fire

The main advantages of fire as a vegetation management tool is that a clean burn removes unwanted vegetation, (including pine wildlings, pine cones and seed) and debris after harvesting. Re-establishment of the plantation is therefore easier and cheaper. A fire can kill or stimulate weed seed germination, whereafter seedlings can be controlled chemically (Balneaves *et al.*, 1992 ex Richardson, 1992). Prescribed fires remove forest fuel and thereby reduce the risk of wildfires (Martin *et al.*, 1979). In New Zealand with its higher rainfall, fire is used more frequently than in Australia, the southern U.S.A. and South Africa, with their higher fire risk (Boomsma and Hunter, 1990; Minogue *et al.*, 1991). Fire is a relatively inexpensive vegetation management operation compared to other vegetation management options (Minogue *et al.*, 1991).

The disadvantages of fire as a vegetation management instrument are the loss of nutrients, weed invasion and soil erosion due to fast water run off. Other problems are the risk off the fire "escaping" into neighbouring plantations, negative public opinion and possible environmental damage (Hall, 1993; Minogue *et al.*, 1991; Richardson, 1992).

1.3.6 Oversowing/intercropping

The logic of oversowing is to establish a cover crop so that the crop trees and cover crops are mutually supportive rather than competing with one another. Cover crops should be a more easily manageable vegetation cover than the original weed cover. Nitrogen fixing cover crops have increased in popularity because of increased crop tree productivity, simple rotations, ease of control, reduction of soil erosion and contribution to weed control. In the Central North Island of New Zealand where water seldom becomes limiting for tree growth, oversowing has increased from 6% in 1991, 29% in 1992 to 45% in 1993. (Nambiar and Sands, 1993; Schumann, 1991; Van Rossen and West, 1993). In the Kinleith region in New Zealand, oversowing is done by fixed wing aircraft. Seeds are sown similarly to aerial fertilizer application (Geddes, 1993).

Cover crops compete for water, light and nutrients. Therefore covercropping is not recommended where resources become limiting. Cover crops should be removed before tree growth is impaired (Eccles and Little, 1995). Perennial cover crops should therefore not be planted where the available soil water becomes restricted. Intercropping *P. radiata* with annual lupins, which die in the dry summer, showed increased tree growth and soil nitrogen reserves (Nambiar and Sands, 1993). In some cases oversowing does not inhibit weed growth sufficiently, spot herbicide treatment is then used for tree release (Eccles and Little, 1995; Zabkiewicz, 1992). Schumann (1991) reported that *Vigna sinensis* (cowpea), planted fourteen days after *Eucalyptus* hybrids in Zululand, resulted in severe competition pressure. *Mucuna pruriens* (velvet bean) was found unsuited because of its climbing nature.

1.3.7 Biological

1.3.7.1 Grazing

Animals used for grazing include cattle, sheep, goats and pigs. Grazing can be a very effective and lucrative vegetation control option, but requires additional farming skills not always possessed by foresters. It can be practised in compartments with low initial stocking (Pearson, 1981 ex Minogue, 1993). Grazing should start before weed dominance occurs and when trees are one to two years old. Silvicultural concerns with grazing include soil compaction, soil disturbance and damage to trees. Suitable live stock must be found that will utilize the weed vegetation in preference to crop trees. Therefore, the weed vegetation must be palatable in preference to crop trees. Water must be available to the animals and additional fencing will be required. The initial costs to start such an operation are high. All forest sites are not suitable for grazing either (Balneaves and McCord, 1990 ex Richardson, 1992; Minogue *et al.*, 1991; Richardson, 1992).

Richardson (1992) reported that successful grazing has been implemented in both Australia and New Zealand. In South Africa, *P. radiata* plantations are grown where fynbos is the natural vegetation. This vegetation is not high in nutrients and therefore not suitable for grazing.

1.3.7.2 Mycoherbicides

Mycoherbicides can be defined as fungal pathogens that are used to control weeds. In Australia and New Zealand no mycoherbicides are available for use in forestry (Richardson, 1992). To my knowledge there are no mycoherbicides available for use in *P. radiata* plantations in South Africa either.

Mycoherbicides are developed from natural pathogenic fungi of the weed species. This form of weed control is inexpensive compared to chemical herbicides. They are as a rule host specific, making them selective to the target weeds only. Mycoherbicides can be used in conjunction with chemical herbicides. Extreme care must be taken that the crop species are totally resistant to pathogens selected for use as herbicides (Ayres and Paul, 1990).

1.4 Crop response to vegetation management

Herbaceous weed control, irrespective of duration (one or two years) or method (inter-row or total area), increased height of *P. taeda* at age nine years (Lauer *et al.*, 1993). Similarly, Quicke *et al.* (1995) found dbh, basal area and volume increases where herbaceous vegetation was controlled for two years in *P. taeda* stands. Brown (1989) stated that no tree crop would exist without weed control. Most weed control treatments during the first two years resulted in at least a 25% increase in volume at age nine (Lauer *et al.*, 1993). Various studies overseas have shown growth gains from vegetation management, e.g. *Abies balsamea* produced a 64% volume increase, when released from herbaceous weeds (MacLean and Morgan, 1983 ex Richardson, 1989). *Pseudotsuga menziesii* showed a 260-405% basal area increase ten years after treatment (Radosevich *et al.*, 1976 ex Richardson 1989). Gous (1995) found a 40% increase in both height and diameter growth of two year old *Pinus radiata*. Butcher (1980) found a sixteen percent volume loss of *P. pinaster* through competing vegetation. From the above data it is clear that considerable crop growth gains can be expected from vegetation management.

1.5 Economics

Limited data are available on long term effects of vegetation control on *Pinus* release from competing vegetation. Such data are important to quantify economic thresholds for weed control treatments (Balneaves and Christie, 1988; Busby, 1988; Cain, 1991). To make a return on investment from forestry, expected earnings from capital expenditure, especially early in the rotation, must result at least in sufficient timber increase to break even with the costs (De Laborde, 1991). Generally, the costs of controlling woody weeds are higher than the costs of controlling herbaceous weeds (Dangerfied and Merck, 1988). Spot release from competing vegetation can result in an economic gain, because only a small percentage (depending on initial stocking) of the total plantation area is treated (Zabkiewicz, 1989). The decision between using manual weeding versus chemical weed management, is largely dependent on the cost of labour. In third-world countries, manual weeding is encouraged to provide social welfare programs. In first-world countries, vegetation management practices are reversed due to high labour costs and low labour availability (Zedaker and Glover,1993).

1.6 Research needs/future developments

Future research with chemical pesticides will have to address the following topics: environmental destiny, refinement of rates, optimization of spot treatments, improvement of application methods, weed crop interactions, human health risk and economic viability of herbicide treatments (Gjerstad *et al.*, 1993; Richardson *et al.*, 1995; Versteeg, 1992). Genetic engineering of *P. radiata* to make it selective towards specific herbicides is currently underway in New Zealand at the FRI (Walter *et al.*, 1995). More work on other forestry crop species is needed. Minimal-disturbance site preparation with reduced herbicide rates should be further investigated (New, 1993). Plantation establishment or vegetation management decision-support-systems software, should be developed for micro computers. In these models experience of many experts can be captured, resulting in very powerful decision-support systems (Mason, 1993; Mason, 1995). Granular herbicides are very new to South Africa and will require a great deal more research.

1.7 Conclusions

A consistent increase in the global use of pesticides is predicted, despite intensive efforts to introduce biological and integrated pest control practices (Food and Agriculture Organization, 1990). Zabkiewicz (1989) predicted that herbicides would continue to be an essential tool for vegetation control, although not the only one. Therefore, chemical vegetation management should be practised to cause as little detrimental impact on the environment as possible.

P. radiata plantations in Australia, New Zealand and South Africa are all invaded by similar herbaceous weeds. These weeds compete for scarce resources with the crop trees. Weed management should be designed to accelerate tree growth. Therefore, weeds should be controlled, particularly in one to two year old plantations (Wagner *et al.*, 1995). The herbicides most commonly used for vegetation control in these plantations are: Glyphosate @ approximately 1500g a.i./ha; Hexazinone @ approximately 2000g a.i./ha; Simazine @ approximately 4000g a.i./ha and Terbuthylazine @ approximately 4000g a.i./ha. Total area application should be replaced by spot or strip application, to reduce costs and to be more environmentally safe (Zabkiewicz, 1989).

Allen *et al.* (1995) suggest that *P. radiata* plantations are not "biological deserts". They recorded 147 plant species in a third rotation plantation where herbicides had been used. Sullivan *et al.* (1995) found no differences in small mammal communities between herbicide treated plots and control plots, over a five year period. Similarly, no difference was found within herbaceous weed populations (Sullivan *et al.*, 1995). Lautenschlager *et al.* (1995) concluded that herbicides can create specific habitats for a variety of wildlife.

Weed control has the effect of shifting the growth curve back along the time axis. Therefore, in plantations with weed control, reduced rotation lengths can produce the same volume of timber than the same unweeded plantation, if severe mortality does not occur (Richardson, 1989; Schumann, 1991). From literature it is clear that in most cases forest vegetation management resulted in improved tree growth and survival, with considerable economic earnings.

2. Hexazinone weed control in re-established *Pinus radiata* plantations

Synopsis

The effects of two formulations of hexazinone at two rates with two application methods (1.5m wide strip and total area) on fynbos were tested in a one year old *Pinus radiata* stand. Total manual weeding and mechanical ring weeding of one metre radius were added as experiment treatments to obtain ten treatments. Tree height and diameter growth were monitored to determine the effect of weed control. After 13 months the liquid formulation of hexazinone was significantly better than the powder formulation. There were no significant differences between the two application methods. The higher herbicide rates showed better weed suppression than the lower rates although non-significantly so. Floristic surveys conducted over a three year period indicated satisfactory weed suppression. Plant moisture stress measurements in the first three summers (dry season) after application indicated that the trees were not under water stress.

2.1 Introduction

Forest vegetation management is the discipline where unwanted invading plants are managed, especially in young plantations (Radosevich and Knowe, 1992). From a forester's viewpoint, weeds are plants invading a plantation, causing growth reductions. Weeds recover quickly from disturbance caused by harvesting and site preparation (Goodall *et al.*, 1989), causing financial and physical problems. Weeds can compete severely with plantation trees for water, nutrients and growing space (Busby, 1988), causing slower tree growth (Sands and Mulligan, 1990) and up to 40% increase in tree mortality (Nambiar and Zed, 1980). Nutrient uptake (especially that of nitrogen) can be reduced through direct competition, thus causing a decrease in tree growth (Nambiar, 1989). Access to plantations is hampered by dense growing weeds, which impede silvicultural treatments. Proper weed control increases volume production (Glover *et al.*, 1987 *ex* Busby, 1988) and can thereby improve the profit margin.

The 'standard' method of weed control in south western Cape pine plantations were a mechanical cleaning of one metre radius around the tree (Donald, 1986). Increases in labour costs necessitate the search for alternative weed control methods

(Lyle, 1981). The use of chemical versus mechanical weeding is highly dependent on the cost of labour (Zedaker and Glover, 1993). Darrow (1994) stated that South Africa is not a country of cheap labour. Chemical weed control is less labour intensive, often less expensive (Campbell, 1990) and in many cases gives longer and more effective control than mechanical weeding. Therefore, its use has increased in recent years (Donald, 1986; Zedaker and Seiler, 1988) and will probably continue to do so in the future.

The trial was conducted in a one year old re - established *Pinus radiata* stand in an ex-fynbos community (Acocks, 1988). The effect of chemical and mechanical weed control on growth of *P. radiata* was tested in search for an alternative to mechanical weed management.

2.2 Materials and methods

The trial area is located in the Delheim plantation (33° 52' S; 18° 53' E), approximately 18 km north-east of Stellenbosch, with a 10° western aspect on an Oakleaf soil type (Soil Classification Working Group, 1991) with a mild, moist winter; and hot dry summer (Csa) according to the Köppen formula (Koeppe and De Long, 1958).

The experiment was laid out as a randomized complete block trial with five replicates and ten treatments. Plot size was $54 m^2$ (9 m x 6 m) with nine trees per plot. The total area was burned after harvesting, prior to establishment.

Chemical treatments included two formulations of Hexazinone (liquid and powder), each at two rates and each rate in either a strip (1.5m wide) over the trees or as a total area spray. Strip treatments were applied with the same concentration as those applied to the total area and therefore, the same volume of diluted herbicide, treated twice the area. Mechanical treatments were a total weed removal and a mechanical ring weeding of one metre radius around each tree. Table 2.1 lists the active ingredient (a.i.), amount, trade name and price of the herbicide used. The herbicide was diluted with clean water and applied by knapsack sprayer with a standard "TK2" - brass nozzle, at 300ℓ solution per applied hectare. The weather during spraying was cool (approximately 18°C) with a light southerly wind.

Table 2.1: Herbicides, formulations, trade names, a.i. applied and cost/ha

Herbicide (a.i.) and *Trade name*	**Formulation per hectare**	**a.i./ha (g)**	**Price/ℓ June 1995**	**Herbicide Cost/ha**
Hexazinone (240g/ℓ) *Velpar liquid*	4.00 ℓ 6.00 ℓ	960 1440	R39.60	R158.40 R237.60
Hexazinone (900g/kg) *Velpar powder*	1.0 kg 1.5 kg	900 1350	R128.00	R128.00 R192.00

Floristic surveys were carried out a week prior to herbicide application and twice thereafter on a yearly basis. Four randomly selected plots of one square metre were investigated in each treatment plot. Weeding treatments were applied in December 1989 when the re-established *P. radiata* plantation was one year and five months old.

Plant moisture stress (p.m.s.) was observed during the three summers of 1990 to 1992. This was done by sampling short shoots predawn when p.m.s. reaches its daily minimum and the plant moisture is in equilibrium with soil water (Cleary and Zaerr, 19??). The sampled material was immediately packed on ice to prevent loss of water. Thereafter the p.m.s. was determined with a pressure bomb.

Tree heights were measured to the nearest cm and diameters at 10cm above ground level, to the nearest 0.1mm. The first measurements were taken immediately before treatments were carried out. Nine subsequent assessments were carried out at regular intervals, over a period of 47 months.

A one-way analysis of variance was carried out with height, diameter and p.m.s. as response variables. Height and diameter data were analysed for a sequence of ten enumerations. Linear interactions between rate x area, rate x formulation, formulation x area and formulation x rate x area were tested for their statistical significance. It was followed by Dunnett's two-tailed t-test (Miliken and Johnson, 1984) for the diameter response to test whether any treatment mean differed significantly from the ring weeded control.

2.3 Results

Figure 2.1 shows p.m.s. readings in different seasons to soil water. After the first autumn rains, soil water content increased and p.m.s. decreased due to abundant soil water. Hexazinone at 6M per hectare gave the lowest p.m.s. of all treatments. Treatments with high weed suppression generally gave a lower p.m.s. (Figure 2.2).

There were no significant differences between the treatment means for height, within 47 months after application. For diameter, the hypothesis of equal treatment effects was rejected at a 0.05 level of significance, indicating that at least one of the treatments had a significant effect. Figure 2.3 shows the P-values, i.e. the probability of observing a larger F-value in the ANOVA if H_0 is true, at different points in time.

Mean diameters differed significantly ($\alpha=0.05$) 33 and 47 months after application, indicating that mechanical weeding was superior to chemical weeding. During the same period, liquid hexazinone performed significantly better than powder hexazinone on height growth. Total versus mechanical ring weeding and total versus strip spray disclosed no significant contrasts. Dunnett's two tailed t-test revealed total manual cleaning was significantly better than Hexazinone powder 11 months after application, but this difference was no longer significant after 16 months.

During the first floristic survey the main weed species were: *Metalasia muricata, Hypochoeris radicata, Chrysanthemoides monolifera, Rumex acetocella* and *Helichrysum riveum* (Appendix 2.1).

The second survey revealed that the uncovered area increased from 16% to 28%. The main competitive weeds, namely *Metalasia muricata*, *Chrysanthemoides monolifera* and *Helichrysum riveum*, were adequately controlled by the herbicide. The percentage cover of these weeds decreased considerably over the first year and even beyond that period. The percentage cover of the annuals, especially the Poaceae increased over the same period, from 5.6% in the first survey to 12.8% in the second (Appendix 2.1).

2.4 Discussion

Floristic surveys suggest that some succession occurred. Herbicide application caused annuals, especially grasses, to increase. *Metalasia muricata*, *Chrysanthemoides monolifera* and *Helichrysum riveum* were adequately controlled by Hexazinone at 6ℓ per hectare. However, an additional 2ℓ per hectare in a later experiment was significantly better than the rates tested in this trial. Hexazinone is an ideal herbicide for over the top application, because it does not harm *P. radiata* at the applied rates. Some species increased due to either having a waxy surface (*Helichrysum crispum*), being pubescent (*Hypochoeris radicata*), or because they grow in a lower strata (*Stoebe africana*) and were possibly sheltered by the overgrowth.

Plant moisture stress data (Appendix 2.2) showed that *P. radiata* trees were not severely stressed. It is generally accepted that plants with a p.m.s. of below three bars are not limited by soil water supply (Cleary and Zaerr, 19??). However, diameter and root growth are reduced by soil water deficit before the rate of transpiration and photosynthesis is significantly affected (Rook *et al.*, 1977). Therefore, although the trees appear to be free of water stress, the growth rate could have been slower than under stress-free conditions.

Although the low p.m.s. values indicated that trees were not stressed for water, plots in which weeds were suppressed most, had the lowest p.m.s. values. Sands and Nambiar (1984) reported that *P. radiata* in the age class seven months to three years, progressively became less water stressed, even in the presence of weeds. This is probably because they can utilize water from deeper in the soil, which is unavailable to the weeds. The 6ℓ/ha hexazinone application gave the lowest p.m.s. values of all treatments. This indicates that in a water stressed environment, this treatment should reduce stress of *P. radiata* caused by fynbos.

Some herbicides require two growing seasons after application to manifest their full effect (Zedaker and Seiler, 1988). However, in this study even after 47 months, chemical treatments had no significant effect on *P. radiata* height growth. Nambiar (1989) and Schumann (1991) found that separate weeding and fertilizer applications may not cause significant responses, but simultaneous application may bring about significant timber volume increases. Hexazinone at 2000g a.i. per hectare should be considered as an alternative. The non - significant responses in growth to the different treatments were possibly due to too small quantities of active ingredient applied (Table 2.1).

Lowery *et al.* (1993) found no significant difference between chemical row weeding and manual spot release in *P. caribaea*. In *P. radiata* no significant difference occured between chemical row weeding and manual spot release. Therefore, chemical row weeding is recommended as it is a cheaper option than manual spot weeding. As no significant differences occurred between mechanical ring weeding and total mechanical weeding, mechanical ring weeding would be a cheaper option if chemical weeding is not used. However Schumann's (1991) studies in *Eucalyptus* hybrid clones in Zululand (summer rainfall) indicated that mechanical ring weeding in grass (0.5m wide) is inadequate, because root competition might still occur. When cost benefits and duration of effect of chemical weeding are considered, chemical weeding appears to be the best method (Table 2.2).

Mechanical ring weeding requires 3 - 4 man days/ha at a cost R40.00 per man day for wages and R40.00 for direct overheads, totalling R80.00 per unit per day (F. Gerber, Forester Kluitjieskraal, pers. comm., 1994). Table 2.2 indicates the required yield (break-even volume) to cover treatment cost exceeding R240.00.

Table 2.2: Treatment costs (including R120.00/ha application costs) and estimated volume increase required for financial break-even

Treatment	a.i./ha	Cost/ha	Break-even volume/ha
Mechanical ring weeding	-	R240.00	Control
Total manual weeding	-	R400.00	4.25m^3
Hexazinone liquid strip	480g	R199.20	-1.08m^3
Hexazinone liquid total	960g	R278.40	1.02m^3
Hexazinone liquid strip	720g	R238.80	-0.03m^3
Hexazinone liquid total	1440g	R357.60	3.13m^3
Hexazinone powder strip	450g	R184.00	1.49m^3
Hexazinone powder total	900g	R248.00	0.21m^3
Hexazinone powder strip	675g	R216.00	-0.64m^3
Hexazinone powder total	1350g	R312.00	1.91m^3

Above figures are based on a mean annual increment of 18 m^3/ha at age 20 years; labour cost at R80.00 per man day; weighted average timber price of R86.04/cubic metre; a real discount rate of 3% and a total volume of 472 cubic metres/ha at clearfelling, age 30 years.

Table 2.2 is based on the following estimated break-even volume:

$$\text{Break-even volume} = \frac{\text{Compounded value at clearfelling}}{\text{Weighted average timber price per m}^3}$$

Where

$R \times 1.03^n$ = Compounded value at clearfelling.

R = cost above R240.00, n= clearfelling age - treatment age.

(H.J.E. Uys, pers. comm., 1994.)

The costs above R240.00 at felling age were calculated with compound interest, r = 3%, between treatment age and clearfelling.

2.5 Conclusions

A 1.5m strip spray over *P. radiata* is recommended, as there were no significant differences between strip and total area sprayed. Hexazinone liquid significantly out-performed the powder formulation by 9.4% in diameter growth and is easier to apply. Hexazinone at 720g a.i. per ha, applied as a strip over *P. radiata* caused no damage to the trees and required $0.03m^3$ less timber than the control for financial break-even. However, research with higher a.i. levels per ha should be investigated. No significant differences occurred between mechanical ring weeding and total mechanical weeding. Plant moisture stress data indicated that *P. radiata* trees were not stressed for water.

Hexazinone, although having been on the market for some years, probably does not get the recognition it deserves. Hexazinone showed much promise for over-the-top application in *P. radiata* plantations in the winter rainfall area. In sensitive areas where herbicides should not be used, mechanical ring weeding would be a cheaper option than total mechanical weeding, but still an effective method.

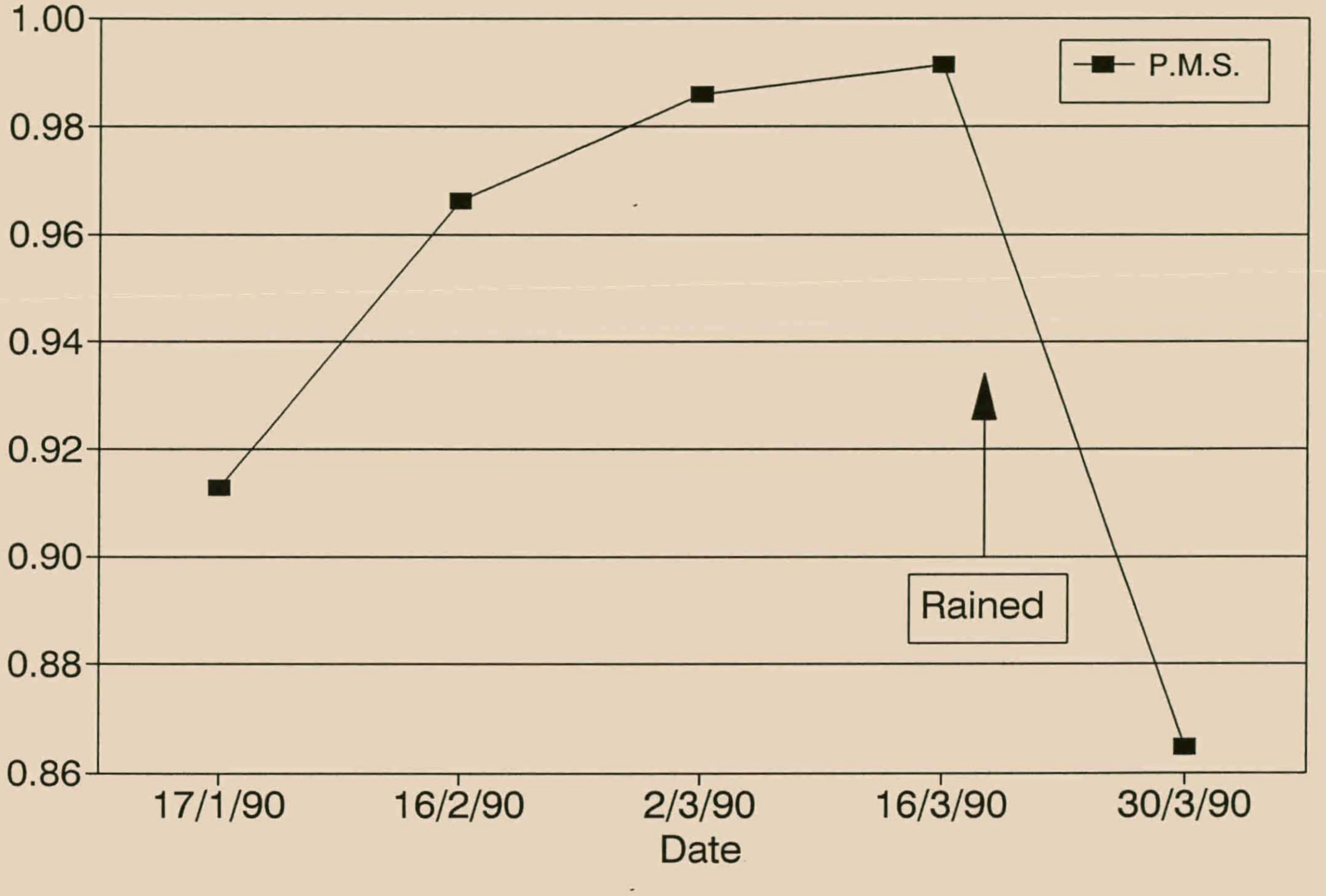

Figure 2.1: Mean P.M.S. of all weeding treatments at Delheim during 1990

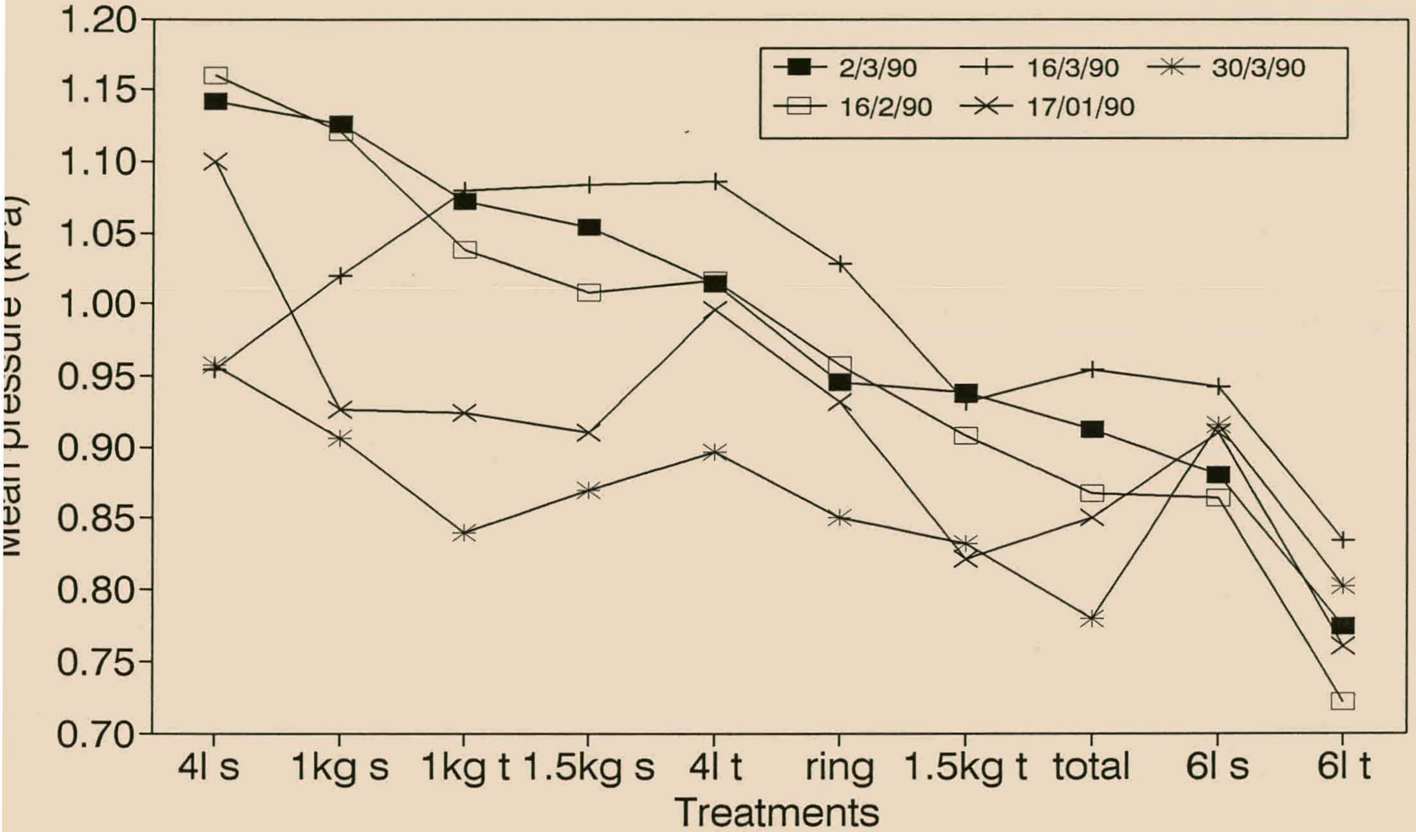

Figure 2.2: P.M.S. for five enumerations during the first summer (1990) after weeding

Key for treatments in Figure 2.2

4 l s	4 ℓ strip 1.5m wide
6 l s	6 ℓ strip 1.5m wide
4 l t	4 ℓ total area
6 l t	6 ℓ total area
1.0kg s	1.0 kg strip 1.5m wide
1.5kg s	1.5 kg strip 1.5m wide
1.0kg t	1.0 kg total area
1.5kg t	1.5 kg total area
ring	Ring weeding
total	Total area weeding

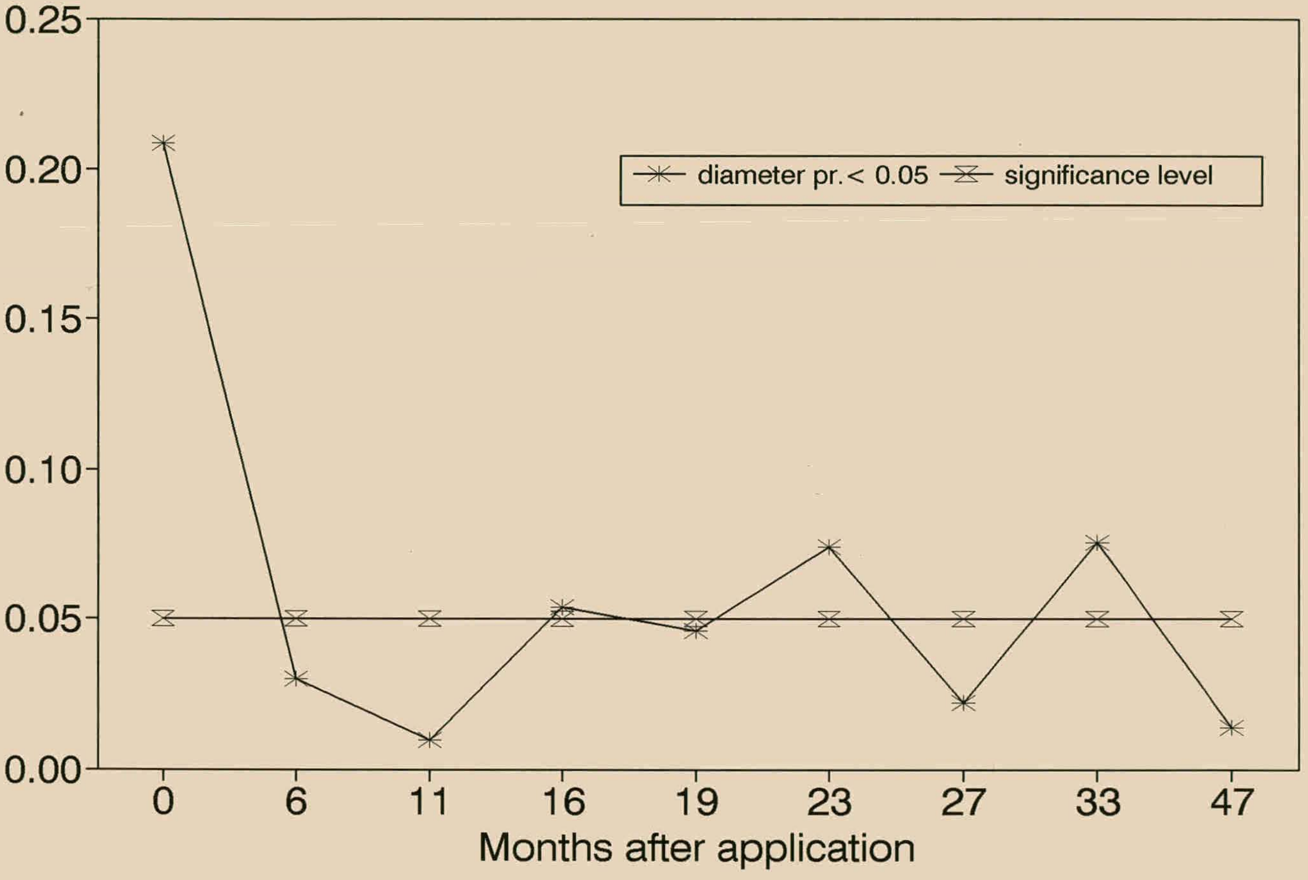

Figure 2.3: Probability of mean treatment diameters at 10cm above ground level differing significantly, Delheim 1989 - 1993

3. A comparative study of five herbicides in re-established *Pinus radiata* plantations

Synopsis

Five herbicides (four plus one mixture) at three rates were tested on fynbos in a 2½ year old *Pinus radiata* stand. A no treatment control, a total manual and a mechanical ring weeding of one metre radius were carried out to complete 18 treatments. Height and diameter increments were observed to determine the effect of weed control. The no treatment control consistently gave smaller height and diameter responses than all the other treatments. Glyphosate at 1500g active ingredient per hectare and hexazinone at 2000g active ingredient per hectare gave significant height and diameter responses. Floristic surveys were conducted over a two year period and indicated satisfactory weed suppression. Plant moisture stress in the first summer after application indicated that the trees were not under severe water stress. However, trees treated with glyphosate were less stressed for water than other herbicide treatments.

3.1 Introduction

Forest vegetation management can be defined as the practice of efficiently channeling limited site resources to the crop rather than associated non - commercial species (Walstad and Gjerstad, 1984 *ex* Richardson, 1992). Weeds affect plantations in one or more of the following ways: they reduce crop growth and / or survival, increase rotation length, decrease product quality, hinder tending and impede stand access (Busby, 1988; Nelson, *et al.*, 1981; Richardson, 1989). It is accepted in plantation forestry that the use of herbicides for weed control is an integral part of management practice (Perrett, 1993). Thompson (1993) stated that there was a deliberate movement away from soil disturbing operations to effective chemical treatment options in New Zealand in the late 1980's.

Hoeing, slashing and hand pulling of natural regeneration were the 'standard' methods of weed control in the south western Cape (Donald, 1986). The tremendous increase in labour costs necessitates the search for alternative weed control methods.

Mechanical and chemical weed control were tested on a two and a half year old re - established *Pinus radiata* (D. Don) stand in an ex - fynbos community. Treatments included a no treatment control, two mechanical treatments and five herbicide treatments, each at three concentrations totalling 18 treatments.

3.2 Materials and methods

The trial area is in the Delheim plantation (33° 52' S; 18° 53' E), 18 km north-east of Stellenbosch, with a 10° western aspect on an Oakleaf soil (Soil Classification Working Group, 1991) in a typical Mediterranean climate. The experiment was laid out as a randomized complete block with four blocks and 18 plots per block totalling 72 plots. Plot size was $54m^2$ (9 m x 6 m) with nine trees per plot.

Treatments were applied in December 1990 when the trees were 2½ years old. The two mechanical treatments included a total weed removal and a one metre radius mechanical ring weeding around each tree. Five herbicidal treatments (four herbicides and one mixture), each at three application rates were applied; an unweeded control was included totalling 18 treatments. Table 3.1 displays the herbicides used, the quantity of active ingredient (a.i.), the price and the treatment cost per hectare. Trees were covered by plastic bags to prevent damage by herbicides which were applied over-the-top, except in the case of hexazinone where trees were unprotected. Herbicides were diluted with clean water and applied by knapsack sprayers with a standard "TK2"-brass nozzle, at 300ℓ solution per hectare. The weather during spraying was cool (approximately 20°C) without wind.

Two floristic surveys were carried out. The first, immediately prior to treatment and the second, one year later (Appendix 3.1). Four square metres were sampled per plot by randomly casting a one metre square and surveying the area. Herbicide effect on weeds was monitored visually.

Plant moisture stress (p.m.s.) was examined during the first summer (January to April 1991) after herbicide application. Short shoots were sampled predawn when p.m.s. is at a minimum for the day and plant moisture is in equilibrium with soil moisture (Cleary and Zaerr, 19??). Collected material was immediately packed on ice to prevent water loss before p.m.s. was determined with a pressure bomb.

Table 3.1: Details related to applied herbicides, trade names, a.i. applied, price and cost/ha

Herbicide & [*Trade name*]	a.i. (g/ha)	ℓ/ha	Price/ℓ June '95	Cost/ ha
Hexazinone liquid [*Velpar*]#	1000 1500 2000	4.16 6.25 8.33	R39.60	R164.74 R247.50 R329.87
Hexazinone & tetrapion [*Frepar*]#	1000 1500 2000	2.72 4.10 5.44	R73.25	R199.24 R300.33 R398.48
Imazapyr [*Arsenal*]#	250 500 1000	1.00 2.00 4.00	R194.92	R194.92 R389.84 R779.68
Glyphosate [*Roundup*]#	1000 1500 2000	2.77 4.16 5.55	R18.50	R51.25 R76.96 R102.68
Glyphosate & imazapyr	1250 1750 2250	3.70 5.10 6.50		R246.17 R277.88 R297.60

Registered trade names

Tree heights were measured with a measuring rod to the nearest cm and diameters at 10cm above ground level were measured, with an electronic calliper, to the nearest 0.01mm. The first measurements were taken immediately before treatments were carried out. Six subsequent assessments were carried out at regular intervals over a three year period.

A one-way analysis of variance, using the SAS (Statistical Analysis Systems) 1985 mainframe computer package was carried out on the height, diameter and p.m.s. data. Height and diameter increment data were analyzed over seven enumerations. Interactions between herbicides and rates were tested. Newman-Keuls' multiple range test was performed on height and diameter increment data to test the difference between treatment means. Dunnett's two-tailed t-tests (Miliken and Johnson, 1984) were performed on the same data to test if any treatment differed significantly from the ring weeded control. The same test was conducted with hexazinone (2000g a.i.) and glyphosate (1500g a.i.) as control.

3.3 Results

The first floristic survey (Appendix 3.1) indicated *Metalasia muricata, Chrysanthemoides monolifera, Helichrysum cripum, Stoebe incana,* and *Helichrysum riveum* as the main weed species. A second survey one year later indicated that the mean uncovered area increased from 10% to 31% (Figure 3.1). The percentage cover of the main weeds decreased considerably one year after herbicide application: *Metalasia muricata* from 10.1% to 4.4%, *Chrysanthemoides monolifera* from 6.6% to 2.8%, *Helichrysum cripum* from 5.6% to 2.3%, *Stoebe incana* from 5.5% to 2.9%, and *Helichrysum riveum* from 3.6% to 1.5% (Figure 3.1). Figure 3.2 shows that glyphosate and hexazinone controlled the weeds more effectively than the other herbicides. The total percentage cover of the annuals, such as the Poaceae, increased from 6.5% to 15.7%.

Ten months after application, significant differences (α=0.05) occurred among treatment means. These differences were maintained until twenty months after application. Newman-Keuls' multiple range test and Dunnett's t-test (Miliken and Johnson, 1984) indicated that 15 months after application, plots treated with 1500g a.i. glyphosate had significantly taller trees than any other plots (Table 3.2). Mean treatment diameters differed significantly from four months after application until twenty months after application (Figure 3.3). Ten months after application, mean height increment of glyphosate treated plots was significantly more than that of any other chemical treatment, with hexazinone in second place (Table 3.3).

Table 3.2: Newman-Keuls' Multiple Range Test on height increment 15 months after application

Weed control treatments (g a.i./ha)	Mean height increment (cm)	
Glyphosate (1500g a.i.)	189.80	a
Hexazinone (2000g a.i.)	144.05	b
Hexazinone (1500g a.i.)	136.15	b
Hexazinone (1000g a.i.)	135.05	b
Glyphosate (1000g a.i.)	132.93	b
Hexazinone & tetrapion (2000g a.i.)	129.08	b
Hexazinone & tetrapion (1000g a.i.)	129.03	b
Control (no treatment)	127.18	b
Glyphosate & imazapyr (1750g a.i.)	126.25	b
Glyphosate & imazapyr (1250g a.i.)	125.05	b
Mechanical ring weeding 1m radius	123.03	b
Imazapyr (250g a.i.)	117.88	b
Total manual cleaning	117.68	b
Hexazinone & tetrapion (1500g a.i.)	116.83	b
Glyphosate & imazapyr (2250g a.i.)	111.75	b
Imazapyr (500g a.i.)	91.18	b
Glyphosate (2000g a.i.)	90.00	b
Imazapyr (1000g a.i.)	86.68	b

Based on Newman-Keuls Multiple Range Test, means not sharing a common letter differ significantly (P = 0.05)

Table 3.3: Pooled height increment within each herbicide 10 months after application

Herbicide	Mean height increment(cm)	
Glyphosate	86.4	a
Hexazinone	70.7	b
Hexazinone & tetrapion	61.5	bc
Glyphosate & imazapyr	52.5	c
Imazapyr	33.5	d

Based on Newman-Keuls' Multiple Range test, means not sharing a common letter differ significantly (P = 0.05)

Significant interactions occurred between herbicides and rates for both height and diameter increment. Dunnett's two-tailed t-test suggested that glyphosate at 1500g a.i. and hexazinone at 2000g a.i. were significantly better than mechanical ring weeding and the control (no treatment) for both height and diameter increment.

Plant moisture stress data (Table 3.4) reflected that *P. radiata* trees were not stressed for water. When p.m.s. is below three bars, plants are generally not limited by soil water supply (Cleary and Zaerr 19??). However, even at average soil moisture stress, transpiration and tree growth diminish significantly (Squire *et al.*, 1987; Rook *et al.*, 1977).

Table 3.4: P.m.s. data (kPa) for four measurements during the summer of 1991

Treatment	18/01/91	15/02/91	15/03/91	05/04/91
Hexazinone 1000g a.i.	1.15	1.00	1.10	0.97
Hexazinone 1500g a.i.	0.95	0.85	0.95	0.87
Hexazinone 2000g a.i.	0.92	0.73	0.85	0.72
Hexazinone & tetrapion 1000g a.i.	1.04	1.48	1.63	0.97
Hexazinone & tetrapion 1500g a.i.	0.96	1.35	1.50	0.92
Hexazinone & tetrapion 2000g a.i.	0.98	1.25	1.40	0.87
Imazapyr 250g a.i.	1.03	1.28	1.38	1.02
Imazapyr 500g a.i.	1.06	1.28	1.40	0.95
Imazapyr 1000g a.i.	1.00	1.18	1.30	0.80
Glyphosate 1000g a.i.	1.00	0.95	1.15	0.83
Glyphosate 1500g a.i.	1.06	0.80	0.98	0.82
Glyphosate 2000g a.i.	0.88	0.73	0.80	0.67
Glyphosate & imazapyr 1250g a.i.	0.89	1.33	1.45	0.78
Glyphosate & imazapyr 1750g a.i.	0.88	1.30	1.48	0.77
Glyphosate & imazapyr 2250g a.i.	0.84	1.25	1.45	0.82
1 Metre mechanical ring weeding	1.02	1.03	1.16	0.91
Total manual weeding	0.95	0.75	0.90	0.76
Control (no treatment)	0.95	1.40	1.68	0.98

Figure 3.4 shows how the average p.m.s. increased from 0.98kPa in the early summer to 1.25kPa later as the soil moisture decreased. After the first autumn rains, soil moisture increased and as a result p.m.s decreased to 0.86kPa. Tukey's studentized range test (Ott, 1988) showed that glyphosate and hexazinone significantly decreased p.m.s. three months after application.

3.4 Discussion

Floristic surveys disclosed that some succession of weed species occurred as annuals increased after herbicide damage. Table 3.5 shows that plots treated with glyphosate and hexazinone had more annuals one year after herbicide treatment, than plots treated with the other herbicides. The reason is that the above mentioned herbicides caused more damage to the fynbos, which as a result started with secondary succession. An increase of annuals strongly suggests that herbicide damage caused succession. Hexazinone gave a longer relief from the main competitive weeds, than the other herbicides. This can be contributed to the residual effect of hexazinone. *Hypochoeris radicata* and *Stoebe africana* increased because they grew in a lower strata and were sheltered by overgrowth at the time of chemical treatment.

Table 3.5: Mean percentage cover by annuals one year after herbicide application, for five chemicals, each at three rates

Herbicide	Percentage cover
Glyphosate	26.1 %
Hexazinone	24.1 %
Glyphosate & imazapyr	10.4 %
Imazapyr	5.3 %
Hexazinone & tetrapion	5.1 %

Glyphosate and hexazinone significantly reduced p.m.s; the reason being that these herbicides sufficiently suppressed the weeds causing less stress on available soil water. Figure 3.5 indicates a strong correlation between weed cover and p.m.s. In a water stressed environment 1500g a.i. glyphosate and 2000g a.i. hexazinone reduced stress on *P. radiata*, caused by fynbos. The glyphosate-imazapyr mixture and the hexazinone-tetrapion herbicide produced inadequate vegetation control.

It can be expected that glyphosate at 1500g a.i. and hexazinone at 2000g a.i. per hectare, applied during summer in *P. radiata* plantations, will significantly improve height and diameter growth, compared to no treatment. Baker (1973) obtained similar results with *P. elliottii* in Florida. This can possibly be ascribed to the decrease in competition for nutrients, light and moisture. Total manual cleaning should also be considered.

The cost of treatments and their effects on tree growth will determine which treatment should be used. Mechanical ring weeding requires 3 - 4 man days/ha at a cost of R40.00 per man day for wages and R40.00 for direct overheads, totalling R80.00 per unit per day (F. Gerber, Forester Kluitjieskraal, pers. comm., 1994). Three man days/ha therefore costs R240.00/ha/weeding. It is generally accepted that this is the minimum weed control required to ensure acceptable growth and survival in re-established *P. radiata* plantations in the Cape. Table 3.6 indicates the required yield increase (break-even-volume) at rotation age 30 years, to cover treatment cost exceeding R240.00.

Table 3.6: Treatment costs (including R120.00/ha application costs) and estimated volume increase required for financial break-even

Treatment	a.i. (g/ha)	Cost/ha (R)	Break-even volume increase (m^3/ha)
No treatment (control)	-	-	-
Mechanical ring weeding	-	240.00	Control
Total manual weeding	-	400.00	4.25
Hexazinone liquid	1000	284.74	1.19
Hexazinone liquid	1500	367.50	3.39
Hexazinone liquid	2000	449.87	5.58
Hexazinone & tetrapion	1000	319.24	2.11
Hexazinone & tetrapion	1500	420.33	4.80
Hexazinone & tetrapion	2000	518.48	7.41
Imazapyr	250	314.92	1.99
Imazapyr	500	509.84	7.18
Imazapyr	1000	899.68	17.54
Glyphosate	1000	171.25	-1.83
Glyphosate	1500	196.96	-1.14
Glyphosate	2000	222.68	-0.46
Glyphosate & imazapyr	1250	366.17	3.36
Glyphosate & imazapyr	1750	397.88	4.20
Glyphosate & imazapyr	2250	417.60	4.72

The above figures are based on a mean annual increment of $18m^3$ at age 20 years, labour cost at R80.00 per man day, weighted average timber price of R86.04/cubic metre, a real discount rate of 3% and a total volume of 472 cubic metres/ha at clearfelling, age 30 years.

Formula used for calculations in Table 3.6:

$$\text{Break-even volume} = \frac{\text{Compounded value at clearfelling}}{\text{Weighted average timber price per m}^3}$$

Where

$R \times 1.03^n$ = Compounded value at clearfelling

R = cost above R240.00, n= clearfelling age - treatment age.
(H.J.E. Uys, pers. comm., 1994.)

The above calculations suggest that glyphosate at 1 500g a.i./ha will require $1.14m^3$/ha less timber over a 30 year period than the ring weeded control for financial break-even. Hexazinone at 2000g a.i./ha, however requires $5.58m^3$/ha more timber than the ring weeded control for financial break-even. In areas of the south western Cape where the m.a.i. is closer to $10m^3$/ha, this treatment might therefore never produce a positive return on investment. From a financial viewpoint, glyphosate at 1500g a.i./ha is the most viable option on relatively low productivity sites.

Differences in weed susceptibility to herbicides can be partly contributed to seasonal effects (D'Anieri *et al.*, 1990). In this study the herbicides were applied in early summer, which may not be the time season for optimum efficacy due to the relatively slow growth rate and subsequent slow translocation of herbicides. This might benefit some herbicides above others, and should be further investigated.

3.5 Conclusions

Diameter and height growth of *P. radiata* were significantly improved by glyphosate at 1500g a.i./ha and hexazinone at 2000g a.i./ha. Glyphosate and hexazinone significantly reduced p.m.s. of *P. radiata*, by suppressing weed growth. At the applied rates, imazapyr produced inadequate vegetation control and suppressed *P. radiata* height growth. Further work to examine the effect of season and the economics of the treatments is recommended. The poor performance of the glyphosate-imazapyr mixture can either be contributed to the detrimental effect that imazapyr has on *P. radiata*, or an antagonistic effect between the two products. The hexazinone-tetrapion herbicide contains too little (only 17%) hexazinone (which is effective on fynbos) to control the vegetation successfully. Tetrapion is a grass herbicide, therefore in fynbos with a small grass component, it is ineffective.

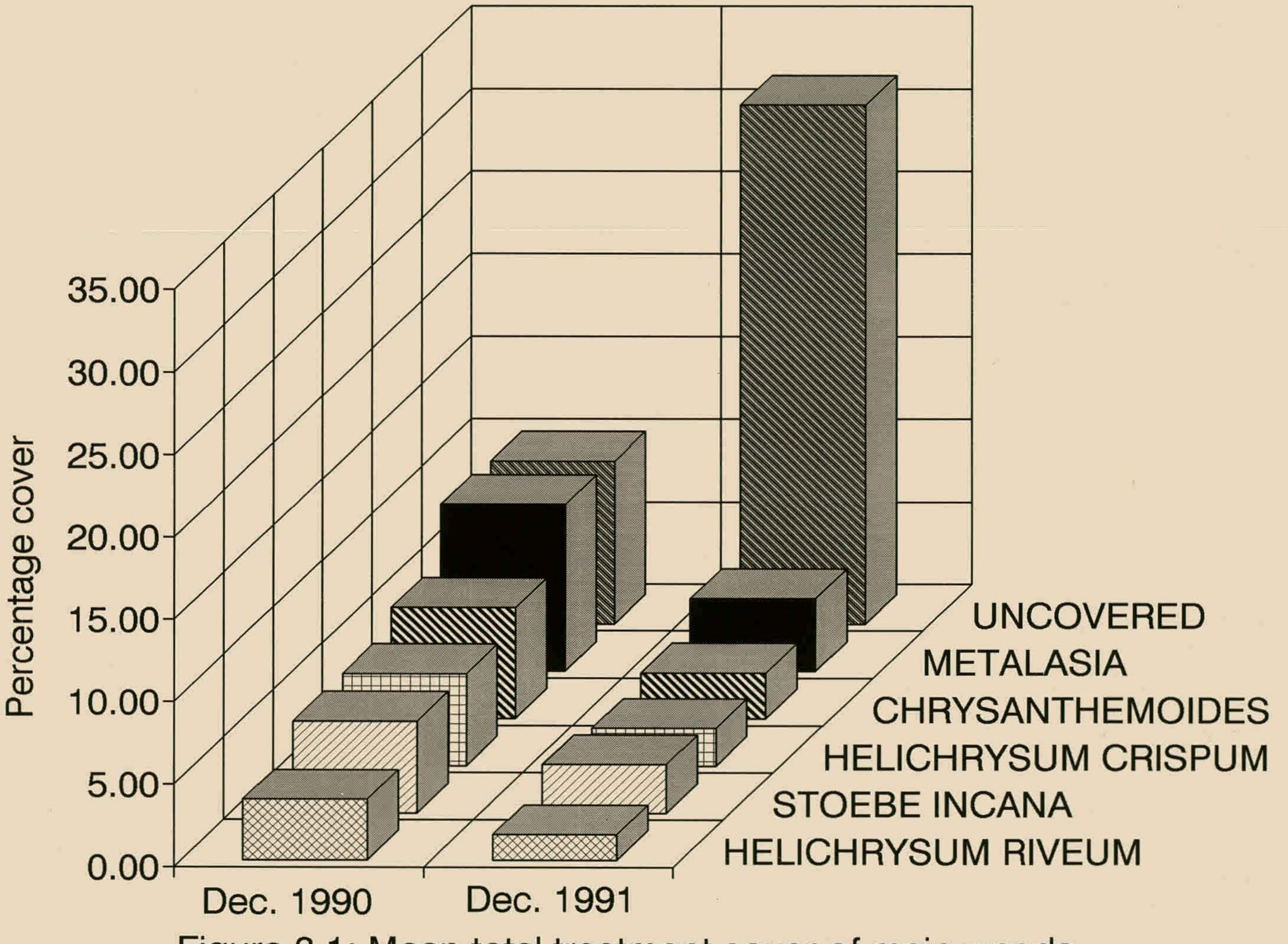

Figure 3.1: Mean total treatment cover of main weeds

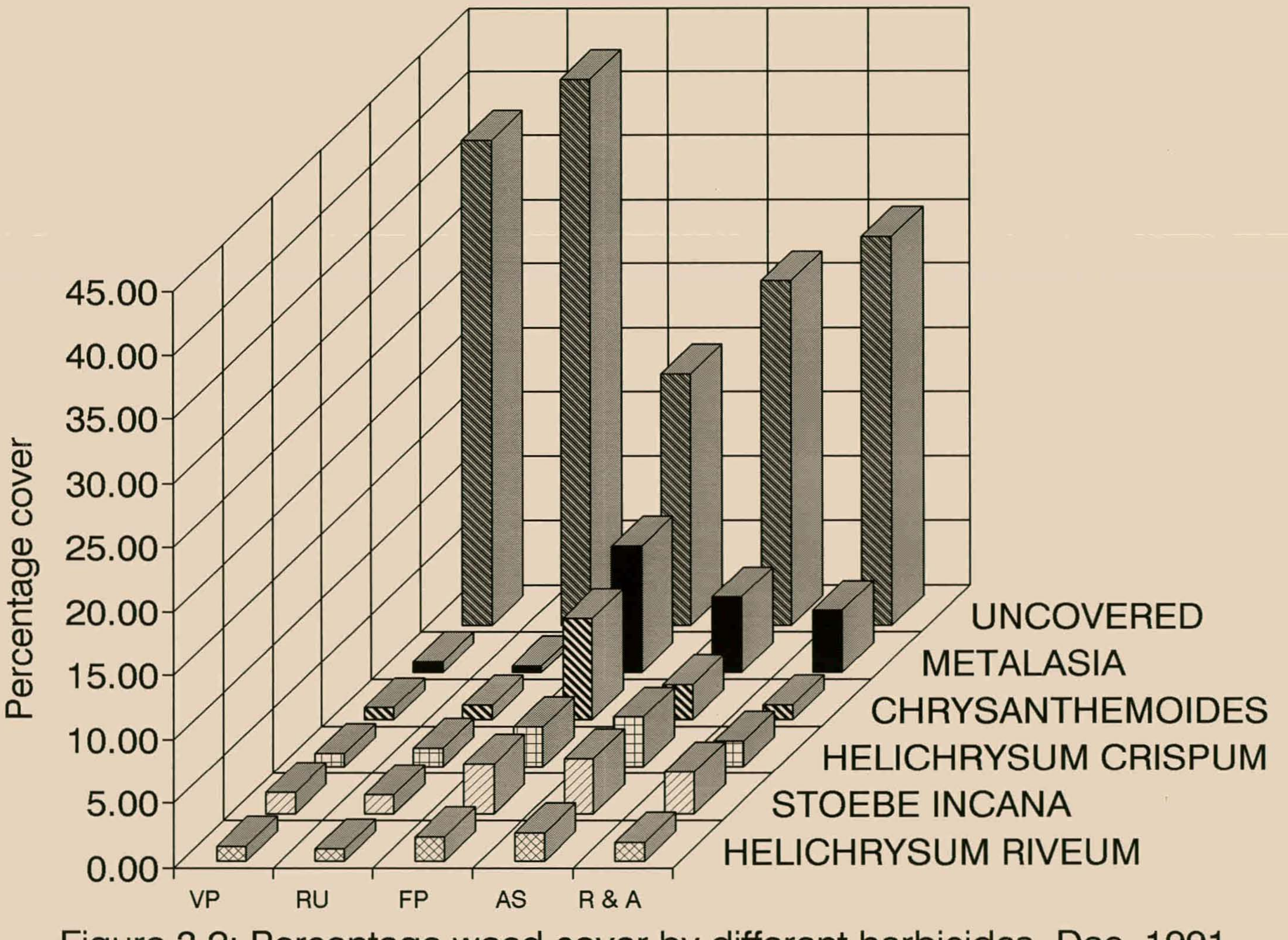

Figure 3.2: Percentage weed cover by different herbicides, Dec. 1991

Key for treatments in Figure 3.2

Abbreviation	Herbicide	Active ingredient
VP	Velpar	hexazinone
RU	Roundup	glyphosate
FP	Frepar	hexazinone & tetrapion
AS	Arsenal	imazapyr
R & A	Roundup & Arsenal	glyphosate & imazapyr

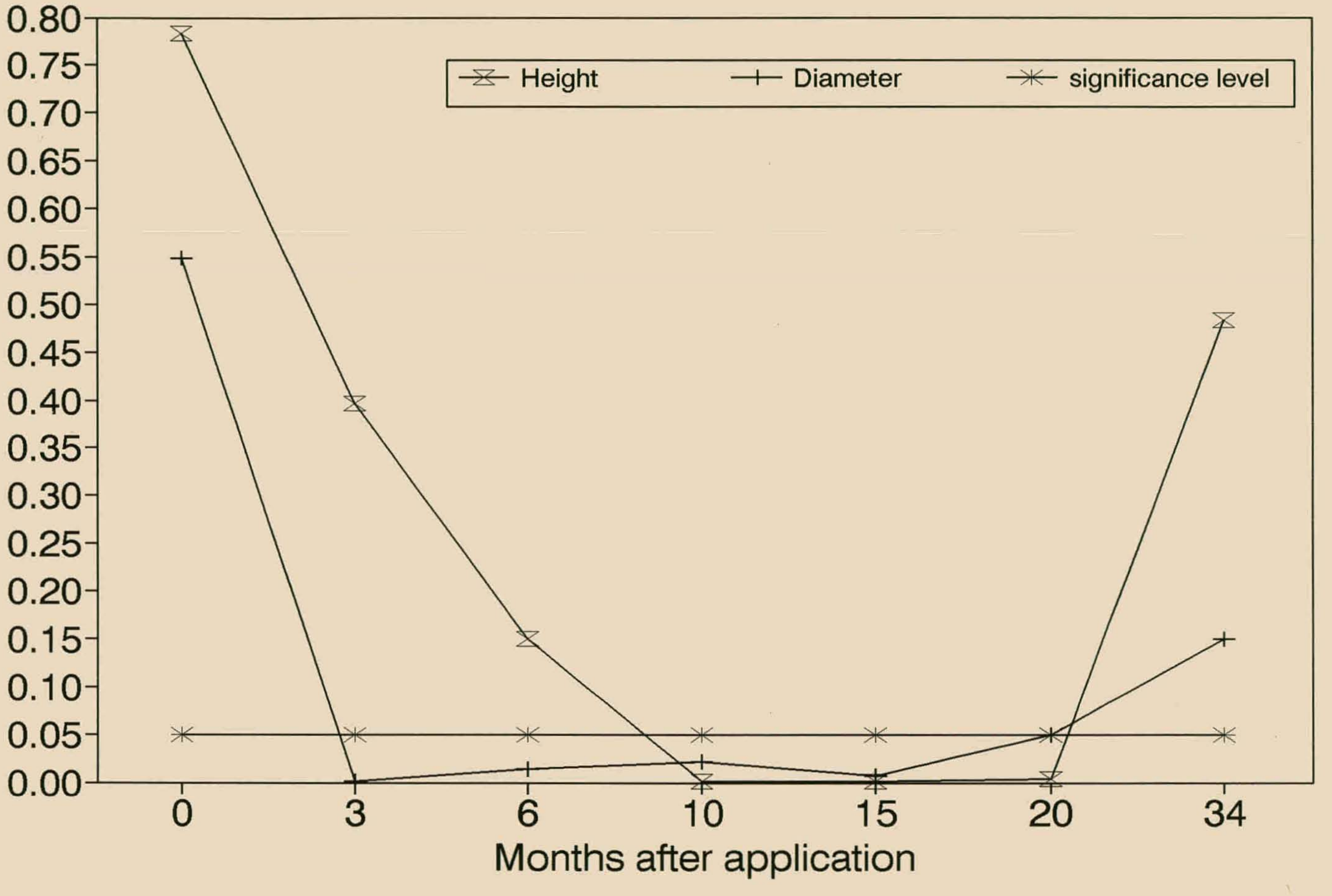

Figure 3.3: Probability of mean treatment heights and diameters differing significantly, Delheim 1990 - 1993

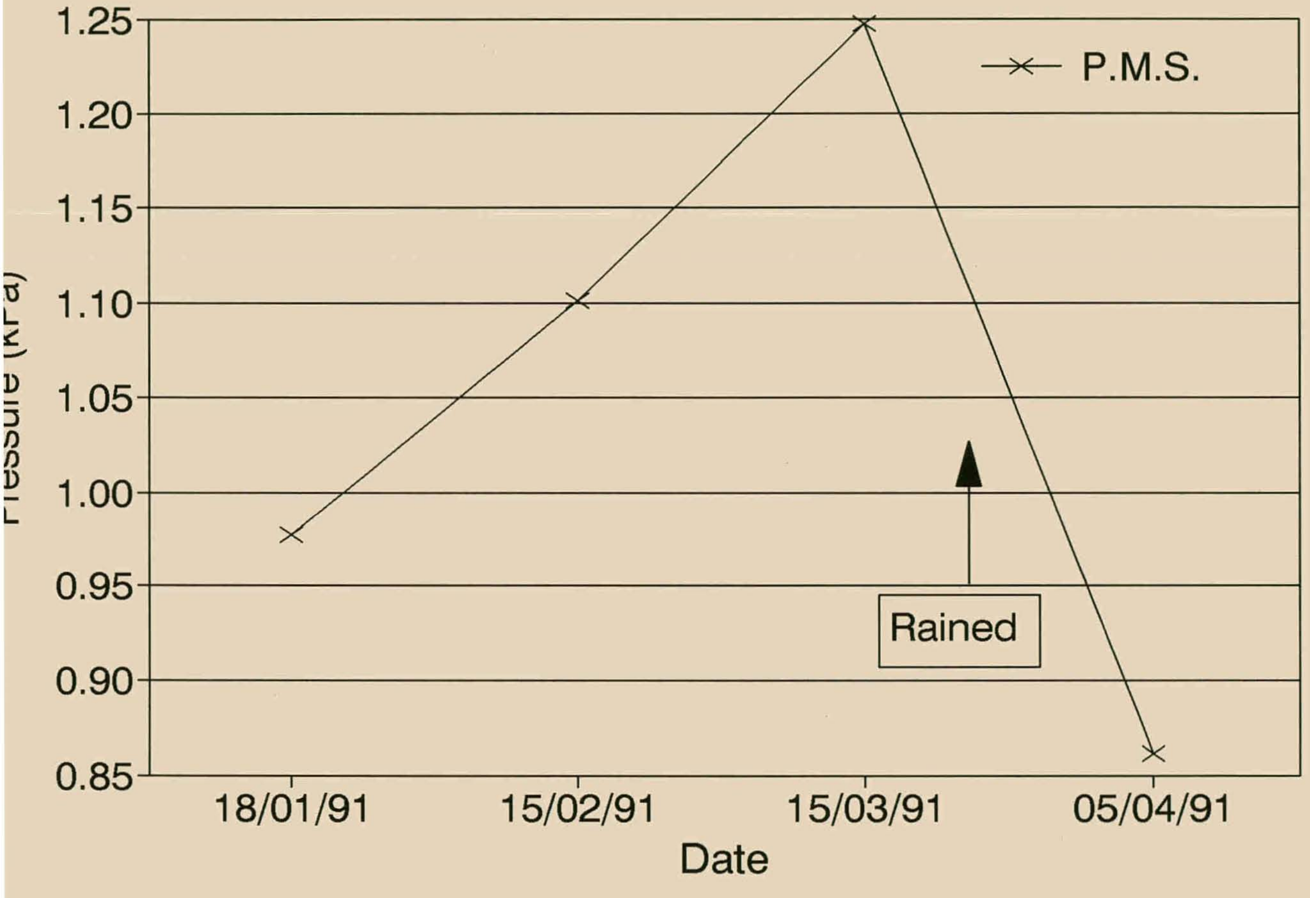

Figure 3.4: Mean P.M.S. for all treatments Jan - April 1991

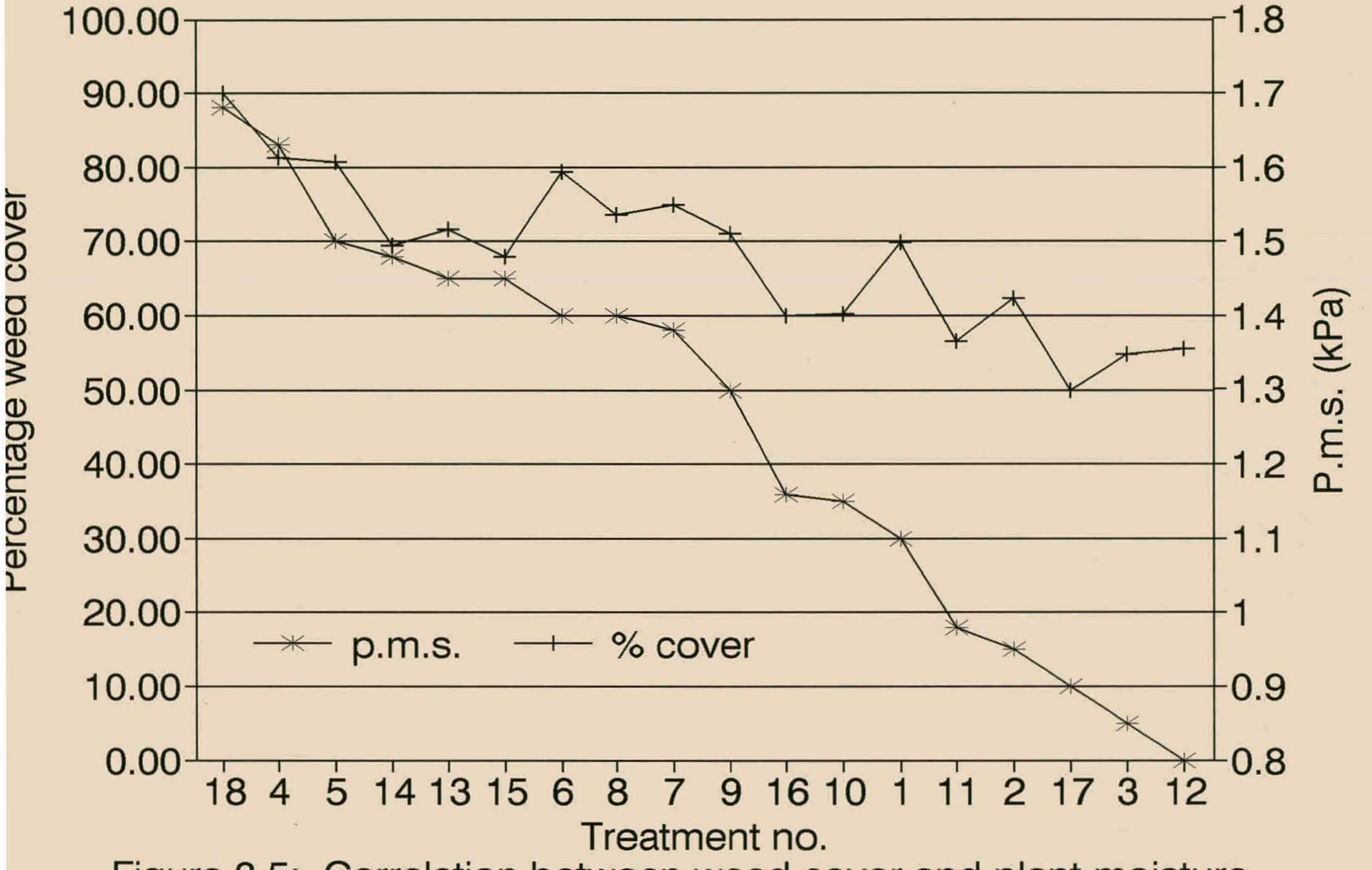

Figure 3.5: Correlation between weed cover and plant moisture stress, R square = 0.81

Key for treatments in Figure 3.5

Treatment no.	treatment
1	Hexazinone liquid @ 1000g a.i./ha
2	Hexazinone liquid @ 1500g a.i./ha
3	Hexazinone liquid @ 2000g a.i./ha
4	Hexazinone & tetrapion @ 1000g a.i./ha
5	Hexazinone & tetrapion @ 1500g a.i./ha
6	Hexazinone & tetrapion @ 2000g a.i./ha
7	Imazapyr @ 250g a.i./ha
8	Imazapyr @ 500g a.i./ha
9	Imazapyr @ 1000g a.i./ha
10	Glyphosate @ 1000g a.i./ha
11	Glyphosate @ 1500g a.i./ha
12	Glyphosate @ 2000g a.i./ha
13	Glyphosate & imazapyr @ 1250g a.i./ha
14	Glyphosate & imazapyr @ 1750g a.i./ha
15	Glyphosate & imazapyr @ 2250g a.i./ha
16	Total manual weeding
17	Mechanical ring weeding (control)
18	No treatment (control)

4. Effect of season of application on herbicide efficacy in virgin establishment of *Pinus radiata* plantations

Synopsis

Three herbicides (glyphosate, hexazinone and metsulfuron methyl) at three rates were tested on indigenous herbaceous shrubs (macchia) in a one year old virgin *Pinus radiata* stand. A mechanical ring weeding of one metre radius was included as a control treatment. Herbicides were applied over-the-top to uncovered *P. radiata*. These treatments were tested for each of four seasonal applications. Tree height and diameter growth were measured to determine efficacy of the treatments. Two floristic surveys indicated satisfactory weed suppression.

Summer was the best season to apply herbicides. Glyphosate and hexazinone were significantly better than metsulfuron methyl. Hexazinone had no detrimental effect on *P. radiata* and improved their height growth, whereas glyphosate scorched the trees, but improved their diameter growth.

Optimum application rates of these herbicides are 2000g and 1500g active ingredient (a.i.) hexazinone and 1500g a.i. glyphosate per hectare.

4.1 Introduction

Weeds can reduce crop growth and survival, increase rotation length, decrease product quality, hinder tending and impede stand access (Busby, 1988; Nelson *et al.*, 1985; Richardson, 1989). Weed control is the single most important treatment to improve tree growth (Richardson, 1992). The effect of treatments on growth is related to the amount of weed suppression (Radosevich and Knowe, 1992), with maximum crop production invariably occurring in absence of competing weeds (Cousens *et al.*, 1987 ex Radosevich and Knowe, 1992). Generally, weeding is not required after canopy closure (Nambiar, 1989). Therefore, weed management should be designed to accelerate tree growth.

In trials with various herbicides it became apparent that season of application plays a vital role in herbicide efficacy. Schumann (1990), spraying, 1500g a.i./ha in spring and summer and Harrington (1993), spraying 900g a.i./ha in spring, found that hexazinone caused burning of *Pinus patula* and *P. radiata* respectively. Donald

(1986) and Gous *et al.* (1992), spraying in summer, found that 2000g a.i. hexazinone caused no damage to *P. radiata*. Thompson (1993) used 4320g a.i. glyphosate per hectare to control herbaceous weeds. Donald (1986) found that an application of 2160g a.i. glyphosate per hectare in summer had minimal effect on macchia vegetation. However, Gous *et al.* (1992) found that 1500g a.i. glyphosate, also applied in summer, successfully controlled macchia vegetation. These contradicting results led to the establishment of a trial in the southern Cape.

Hoeing, slashing and hand pulling of natural regeneration were the 'standard' methods of weed control in the south western Cape (Donald, 1986). Mechanical ring weeding combined with slashing of large weeds between rows, is the most cost effective mechanical weeding method (Lowery *et al.*, 1993). Schumann (1992a) found mechanical ring weeding to be effective in grass infested *Eucalyptus* plantations in Zululand.

In the late 1980's, Thompson (1993) observed that in New Zealand, there was a trend away from soil disturbing operations towards effective chemical treatment options. In South Africa, soil preparation, especially for re-afforestation, has recently become less intensive, with the result that weed control may become more important. Donald (1986) reported that wages in the southern and western Cape increased from R1.00/unit in 1970 to R15.00/unit in 1986. Today (1995) that same unit cost is R40.00 (C. Bekker, personal communication, 1995) for wages and R40.00 for direct overheads, totalling R80.00 per unit per day. The tremendous increase in labour costs necessitates the search for alternative weed control methods (Lyle, 1981; Gous *et al.*, 1992).

4.2 Materials and methods

The trial was conducted in the southern Cape near Plettenberg Bay on the timber farm, Wynanskraal. The trial area has Sterkspruit and Kroonstad soil forms (Soil Classification Working Group, 1991), a 10-15^0 northern aspect and a mean annual rainfall of 650 mm. According to the Köppen (Koeppe and De Long, 1958) formula, the site has hot summers, mild winters and all months are moist. The site has a predicted mean annual increment (m.a.i.) of 8 m^3/ha (L. Viljoen, pers. comm., 1994).

Herbicides were applied at the end of March, June, September and December 1992. Three herbicides (glyphosate, hexazinone and metsulfuron methyl), each at three rates, were tested on indigenous herbaceous shrubs (macchia) in a one year old virgin *P. radiata* stand. A mechanical ring weeding of one metre radius was included as a control treatment. Herbicides were applied over-the-top, to uncovered one year old *P. radiata* established in macchia community, as this is the most economical and practical way of applying herbicides (Nelson *et al.*, 1985).

The experiment was established as a randomized complete block with three blocks. Each block contained ten treatments nested within four seasons, totalling 40 plots. Table 4.1 displays the herbicides used, the quantity of active ingredient (a.i.), the price and the treatment cost per hectare. Herbicides were diluted with clean water and applied by knapsack sprayers with a standard "TK2"-brass nozzle, at 300ℓ solution per hectare. Plot size was 180 m² (15m x 12m) with 24 trees per plot, of which the centre eight were measured. Espacement was 4m x 3m, with 833 stems/ha at time of planting. Blanking was carried out 3 months after initial planting.

Table 4.1: Herbicides, trade names, a.i. applied, prices and herbicide costs/ha

Herbicide and *Trade name*	**Product quantity applied/ha**	**a.i. (g/ha)**	**Unit price in June '95**	**Cost/ ha**
Hexazinone powder [*Velpar*]	1.11kg 1.66kg 2.22kg	1000 1500 2000	R128.00	R142.08 R212.48 R284.16
Glyphosate [*Roundup*]	2.77ℓ 4.16ℓ 5.55ℓ	1000 1500 2000	R18.50	R51.25 R76.96 R102.68
Metsulfuron methyl [*Escort*]	15.00g 30.00g 45.00g	9 18 27	R1636.00	R24.54 R49.08 R73.62

Two floristic surveys were carried out. The first, immediately prior to the first treatment and the second, two years later, i.e. one year after the last herbicide application. Six plots of one square metre each were randomly selected in each plot. Herbicide effects on weeds were monitored visually at three month intervals.

Tree heights were measured with a measuring rod to the nearest cm and diameters 10cm above ground level (D_{10}), with an electronic calliper, to the nearest 0.1mm. The first measurements were taken immediately before the initial treatments were applied. Seven subsequent measurements of the entire trial were carried out at three month intervals over a two year period.

A one-way analysis of variance was carried out with one year height and diameter increments as response variables. Interactions between herbicide and season were tested for their statistical significance. Dunnett's two-tailed t-tests (Miliken and Johnson, 1984) were performed on height and diameter increment response variables to test if any treatment differed significantly from the mechanical ring weeded control. The same test was conducted with 2000g a.i. hexazinone and 1500g a.i. glyphosate as control.

4.3 Results

The first floristic survey identified *Cynodon dactylon, Ehrharta capensis, Metalasia muricata, Stoebe incana* and *Struthiola stricta* as the main weed species (Figure 4.1). The second survey 21 months later, indicated that the area not covered by weeds in the entire trial increased from 9.2% to 45.9% (Figure 4.1). The percentage cover of the main weeds decreased considerably: *Cynodon dactylon* from 32.6% to 20.4%, *Ehrharta capensis* from 12.2 to 3.3% and *Metalasia muricata* from 12.0% to 5.6%, one year after herbicide application. Figure 4.2 shows that based on uncovered areas, glyphosate and hexazinone controlled the weeds more effectively than metsulfuron methyl. The total percentage cover of the annuals, such as the Poaceae, increased from 6.5% to 15.7%.

For both height and diameter, the hypothesis of a zero difference between treatment effects was rejected at a 0.05 level of significance, indicating that at least one of the treatment means differed significantly from others. Significant differences also occurred between the treatment means for the season in which herbicides were applied.

Table 4.2 shows the % height and diameter increments one year after application for the different treatments. Hexazinone generally gave a better yield than glyphosate and metsulfuron methyl. Hexazinone at 2000g a.i. produced a statistically significant improvement of more than 40% over the mechanical ring weeding control, both in height and diameter growth responses. The second best treatment was hexazinone at 1500g a.i./ha producing 36% and 27% improvements on height and diameter growth respectively.

Table 4.2: Effects of weed control treatments on *P. radiata* height and diameter increments during first year after application

Weed control treatments (g a.i./ha)	% Height increment		% Diameter increment	
Hexazinone 2000g	140.6	a	140.4	a
Hexazinone 1500g	136.2	ab	127.4	ab
Glyphosate 1500g	116.0	b	113.7	abcd
Hexazinone 1000g	113.8	bc	97.3	bcd
Glyphosate 1000g	110.6	c	111.6	abcd
Glyphosate 2000g	105.1	c	118.5	abc
Mechanical ring weeding	100.0	c	100.0	bcd
Metsulfuron methyl 9g	100.0	c	82.2	d
Metsulfuron methyl 27g	98.8	c	116.4	abc
Metsulfuron methyl 18g	95.1	c	91.8	cd

Based on Duncan's Multiple Range Test, means within a column not sharing a common letter differ significantly (P = 0.05)

Figure 4.3 shows the mean tree heights and indicates that hexazinone at 2000g a.i./ha was significantly better (α=0.05) than all treatments except hexazinone at 1500g a.i./ha.

Application of herbicides in summer produced significantly better results than when applied in other seasons (Table 4.3). Summer applications produced an improvement of 38% in height growth, compared to other seasons of application.

Table 4.3: Effect of season of application on height increment during the first year after weeding

Mean height increment (cm)		Season of application
83.41	a	Summer
59.97	b	Spring
55.69	b	Winter
54.11	b	Autumn

Based on Duncan's Multiple Range Test, means not sharing a common letter differ significantly (P = 0.05).

No significant interactions occurred between herbicide treatments and seasons of application. Hexazinone performed significantly better than glyphosate and metsulfuron methyl on height increment as was disclosed by testing relevant contrasts. Linear responses were found within hexazinone and metsulfuron methyl rates. A quadratic response was found within the applied glyphosate rates and indicated that the optimum rate is close to 1500g a.i./ha.

Dunnett's two tailed t-test (Miliken and Johnson, 1984) revealed that hexazinone at 2000g a.i./ha performed significantly better than all treatments except hexazinone at 1500g a.i./ha and glyphosate at 1500g a.i./ha.

4.4 Discussion

Floristic surveys suggested that hexazinone and glyphosate controlled weeds adequately. Nelson *et al.* (1985), using 1980g a.i./ha in Georgia, found a similar response to glyphosate treatment on herbaceous weeds. Application of 1500g a.i. glyphosate requires 1.13m^3/ha less timber than the mechanical ring weeding (control), at rotation age for financial break-even (Table 4.4). However, glyphosate at 2000g a.i. and 1500g a.i. are too high rates for over-the-top application, as it caused die-back of *P. radiata* growing tips in all seasons. Therefore, glyphosate at the above rates is not recommended for aerial application. Knapsack application costs (R120.00/ha) are relatively high compared to aerial application (R30.00/ha) (J. Ackermann, personal communication, 1995). At 1500g a.i. glyphosate, weeds are controlled adequately, making it a viable option provided trees are protected or avoided during spraying.

Hexazinone controlled weeds adequately and based on periodic visual assessments, the effects were longer lasting than those of the other herbicides. Hexazinone, at all rates, inflicted no damage to *P. radiata* when applied over-the-top. Therefore, aerial application of hexazinone is advisable, because of relatively low application costs. Summer applications showed no significant differences between the weed management treatments. However, hexazinone at 2000g a.i./ha was the best treatment, but did not differ significantly from hexazinone at 1500g a.i./ha. Hexazinone at 2000g a.i./ha applied in the other seasons proved to be significantly better than all other treatments. For financial break-even, hexazinone at 2000g a.i./ha treatment requires 4.32m^3/ha of timber (Table 4.4) additional to that obtained from mechanical ring weeding (control), at rotation age. However, for aerial application (R30.00/ha) the above mentioned treatment will require only 1.95m^3/ha of more timber than that of the control, for financial break-even. A linear response was found within the applied hexazinone rates. Higher rates of a.i. should be investigated.

Metsulfuron methyl, applied at rates recommended by the producer, had very little effect on the weeds except for *Rubus* spp. Growing tips of *P. radiata* sprayed with 18g a.i. and 27g a.i./ha metsulfuron methyl developed chlorosis and die-back. Therefore, it would be advisable to avoid over-the-top application. Michael (1985), using 28g a.i/ha metsulfuron methyl, similarly found no growth responses in *P. taeda* and observed damage to the trees. As a linear response was found within metsulfuron methyl, a higher rate of a.i. should be considered, because of the relatively low treatment costs.

Early results indicate up to 40% improvements in height and diameter increments due to chemical weed control, compared to mechanical weeding. No interactions occurred between herbicides and season. Table 4.4 indicates the increase in yield needed at clearfelling to justify the use of herbicides applied at age two years, to obtain break-even volume compared to mechanical ring weeding.

Table 4.4: Treatment costs (including R120.00/ha application costs) and estimated volume increase required for financial break-even

Treatment	a.i. (g/ha)	Cost/ha (Rand)	Break-even volume increase (m^3/ha)
Ring weeding	-	240.00	Control
Hexazinone powder	1000	262.08	0.58
Hexazinone powder	1500	332.48	2.44
Hexazinone powder	2000	404.16	4.32
Glyphosate	1000	171.25	-1.81
Glyphosate	1500	196.96	-1.13
Glyphosate	2000	222.68	-0.46
Metsulfuron methyl	9	144.54	-2.51
Metsulfuron methyl	18	169.08	-1.87
Metsulfuron methyl	27	193.62	-1.22

The above figures are based on a m.a.i. of 8 m^3/ha at age 20; labour cost at R80.00 per man day and weighted average timber price of R86.85/m^3. A real discount rate of 3% and a total volume of 215 m^3/ha at clearfelling (30 years) were used. The costs above R240.00/ha, i.e. the cost of mechanical weeding, were calculated with compound interest (r = 3%) between treatment age and clearfelling.

Formula used for calculations in Table 4.4:

$$\text{Break-even volume} = \frac{\text{Compounded value at clearfelling}}{\text{Weighted average timber price per m}^3}$$

where $R \times 1.03^n$ = Compounded value at clearfelling

R = cost above R240.00, n= clearfelling age - treatment age
(H.J.E. Uys, pers. comm., 1994.)

The phenology of *P. radiata* in the southern Cape is unknown. Figure 4.4 indicates the spring and autumn growth peaks of macchia in the southern Cape. The arrow heads indicate the time of herbicide application. Table 4.3 indicates that summer herbicide application was significantly better than the other seasons of application. The reduced response to herbicide treatment in autumn and winter can be explained by the fact that herbicides were applied during a semi-dormant growth period (Figure 4.4). Therefore, herbicides should preferably be applied just before active growth commences in spring and summer.

The spring application of herbicides occurred towards the end of a growth peak. Herbicide translocation and the subsequent suppression of the weeds take some time. It seems that by the time the weeds were suppressed, the weed growth peak had already ended so that there was mimimal beneficial effect to the trees.

The summer application occurred one month before the autumn growth peak started. Therefore, herbicides could suppress weeds before their autumn growth peak, and thereby cause maximum damage to them, with optimum benefit to the trees.

Macchia vegetation has strong vegetative growth potential, provided roots are not damaged. The herbicides used in this investigation are systemic and therefore killed macchia root systems. Therefore, chemical weed management gave significantly better results than mechanical weeding, which left the roots virtually unharmed.

4.5 Conclusions

Summer was significantly the best season to apply herbicides. However, weed control treatments applied during this season showed no significant differences. In the other seasons hexazinone at 2000g a.i./ha was significantly better than all other treatments, excluding hexazinone at 1500g a.i./ha. Hexazinone at 2000g a.i./ha caused no damage in *P. radiata* plantations when applied over-the-top and can be recommended for aerial application. A linear response was found within the applied hexazinone rates, therefore higher rates should be investigated. Hexazinone gave a longer relief from weeds than the other applied herbicides, as it possesses some residual action.

Glyphosate at the applied rates caused die-back of *P. radiata* growing tips. Therefore over-the-top application is not recommended. Application of glyphosate at 1500g a.i./ha is recommended, if trees are protected or avoided.

Applied rates of metsulfuron methyl, as recommended by the producer, were too low, as shown by the linear response. Higher rates of a.i. should therefore be examined, but the trees will have to be protected.

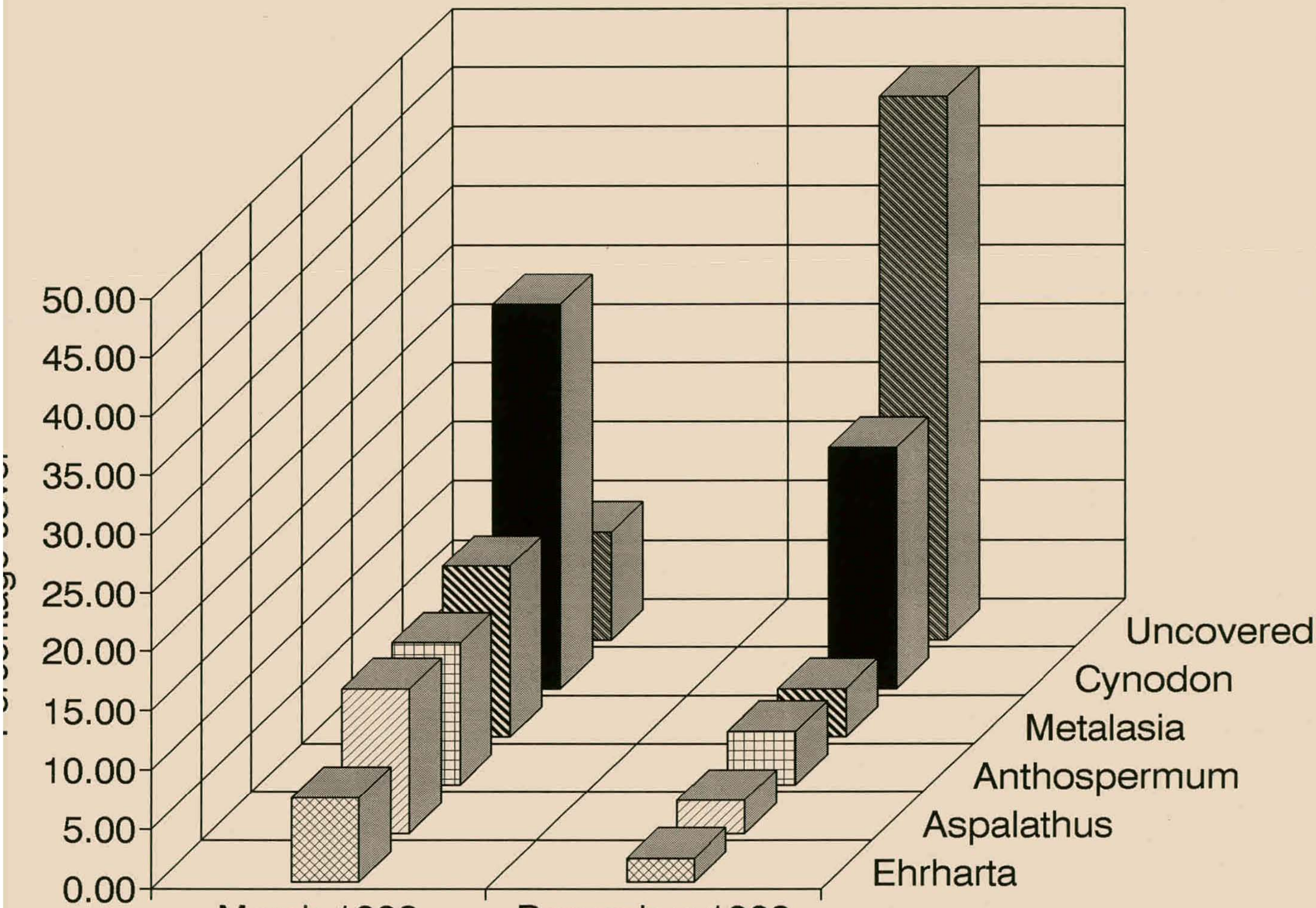

Figure 4.1: Weed cover before herbicide application (1992) and one year later (1993)

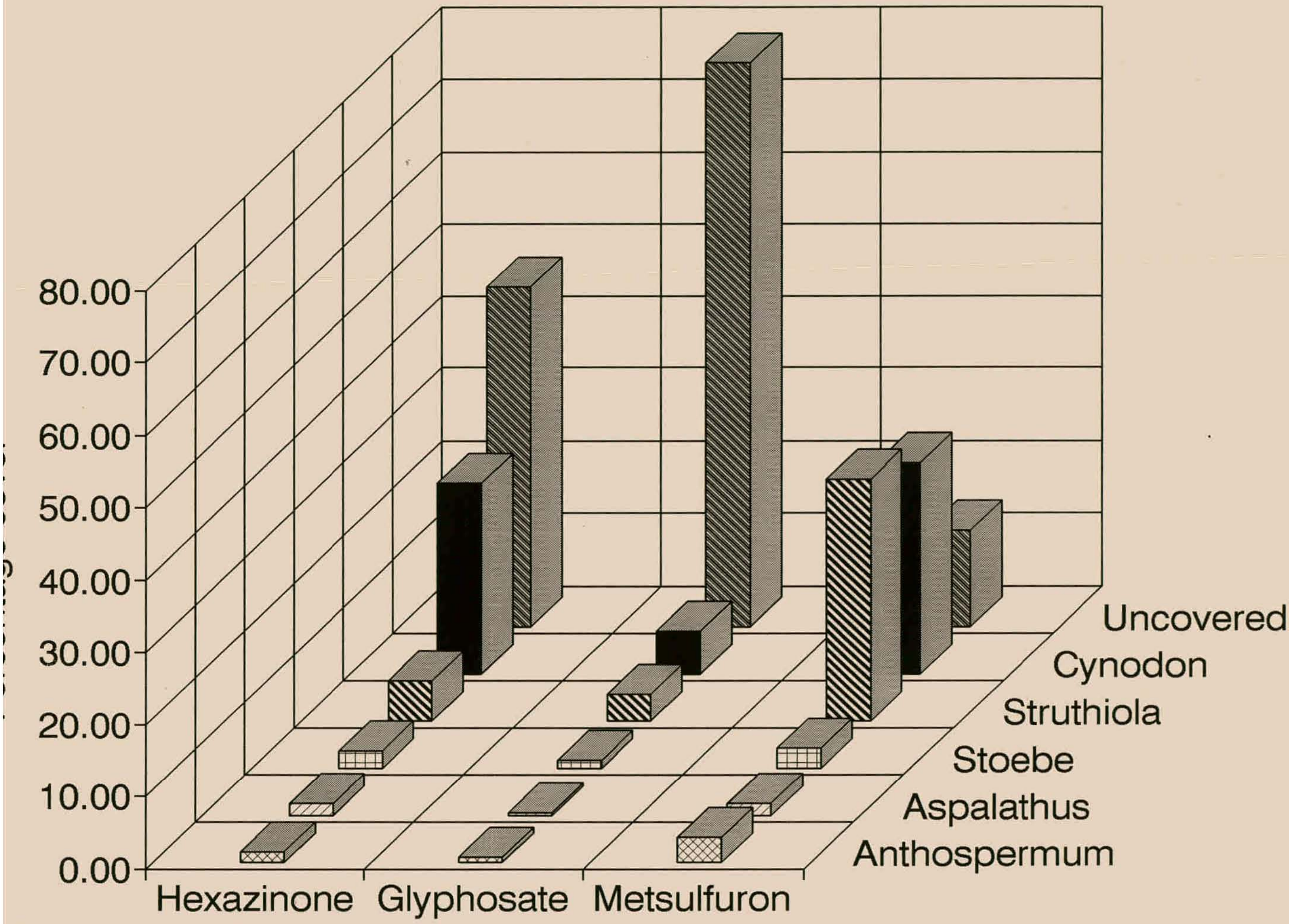

Figure 4.2: Mean effects of herbicides on weed cover one year after application

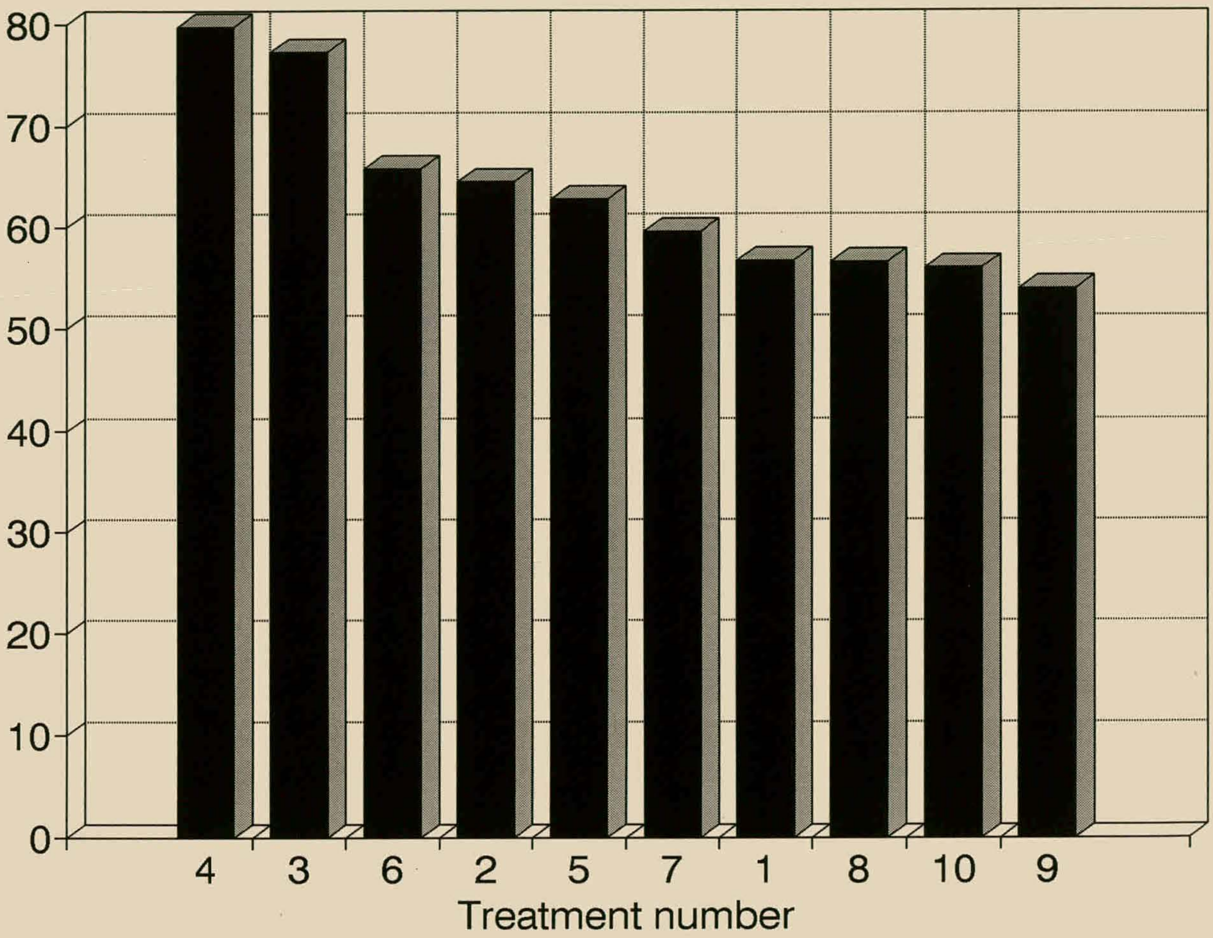

Figure 4.3: One year height increment growth of P. radiata as disclosed by different weed control treatments

Key for treatments in Figure 4.3

Mean height increment (cm)		Weed control treatment	Treatment no.
79.73	a	Hexazinone (2000g a.i.)	4
77.22	ab	Hexazinone (1500g a.i.)	3
65.83	b	Glyphosate (1500g a.i.)	6
64.52	c	Hexazinone (1000g a.i.)	2
62.71	c	Glyphosate (1000g a.i.)	5
59.61	c	Glyphosate (2000g a.i.)	7
56.72	c	Mechanical ring weeding 1m radius	1
56.68	c	Metsulfuron (9g a.i.)	8
56.04	c	Metsulfuron (27g a.i.)	10
56.04	c	Metsulfuron (18g a.i.)	9

Based on Duncan's Multiple Range test, means not sharing a common letter differ significantly (P = 0.05)

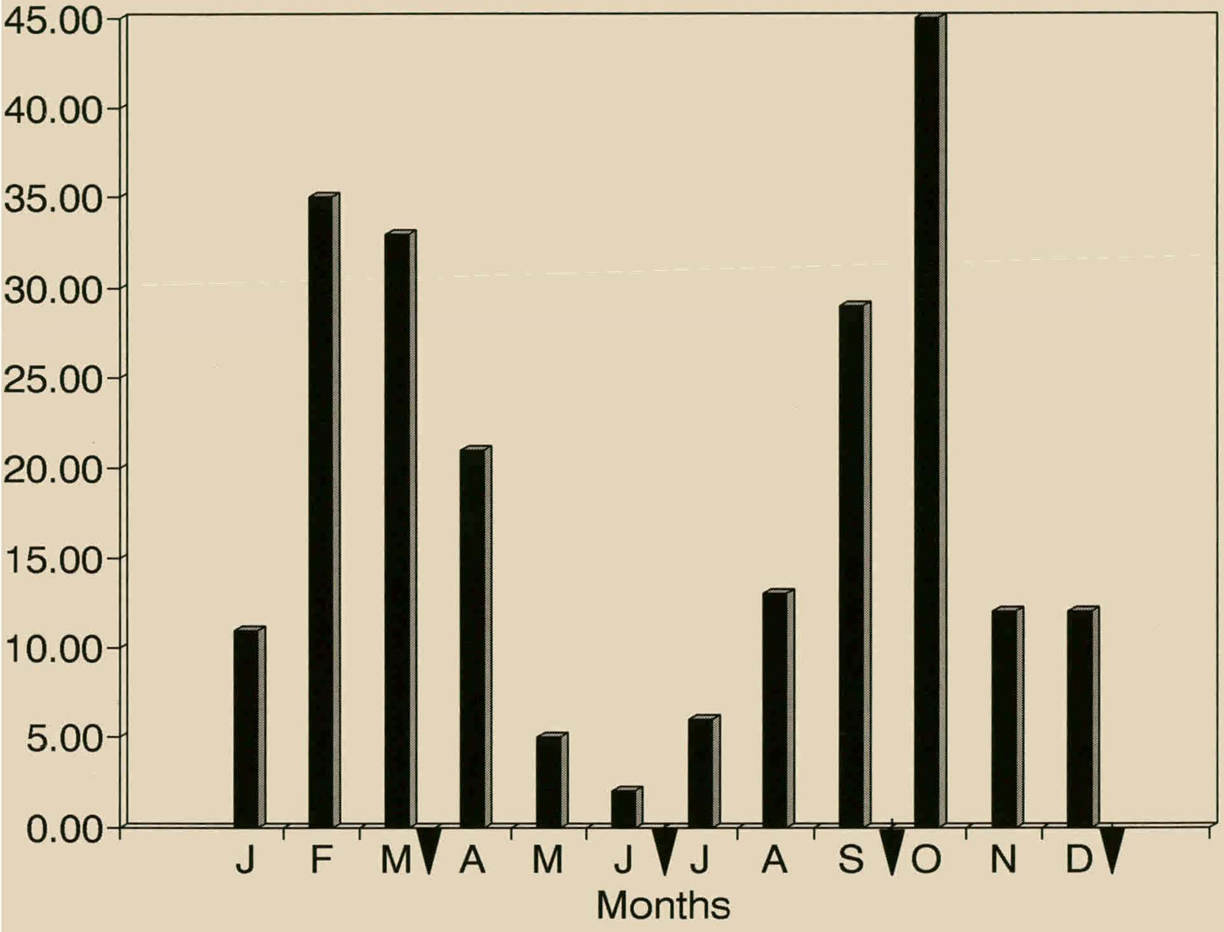

Figure 4.4: Phenogram for south coast Renosterveld as from Pierce (1984). Arrows indicate time of herbicide application

5. Glyphosate weed control in virgin establishment of *Pinus radiata* plantations

Synopsis

Four herbicides, glyphosate in two formulations, thiazopyr and acetochlor were tested on indigenous herbaceous shrubs (macchia/fynbos) in a one year old virgin *Pinus radiata* stand. A mechanical ring weeding of one metre radius was included as a control treatment. Herbicides were applied over-the-top to *P. radiata*. Glyphosate was used as a knockdown herbicide and thiazopyr and acetochlor were added as pre-emergents for each of the glyphosate rates. Tree height and diameter growth were measured to determine efficacy of the treatments.

Glyphosate in the 360g active ingredient (a.i.)/litre formulation (ROUNDUP) was significantly better than the 180g a.i./litre formulation (STING). Glyphosate at the applied rates, 720g a.i./ha, 1080g a.i./ha and 1440g a.i./ha, controlled weeds adequately, but caused damage to the growing tips of *P. radiata*. Therefore, the lowest rate of glyphosate tried (720g a.i./ha), showed significance on height and diameter increments as it caused less damage to the trees than the higher rates (1080g a.i./ha and 1440g a.i./ha). Visual assessments indicated that the addition of pre-emergents to glyphosate gave longer relief from weeds than glyphosate applied without pre-emergents. Weeds recovered quickly from the mechanical hoeing.

5.1 Introduction

As the world population continues to explode, the demand for wood and wood products will rise at an unprecedented rate (Deuss and Foley, 1995; Dyck, 1995). Therefore, progress in forest vegetation management will be essential (Walstad, 1992). South Africa is no exception and therefore the increasing demands for timber and land necessitate that marginal sites are increasingly utilized for timber production. Weeds compete for scarce resources on marginal sites and can reduce the productive potential of a plantation by reducing crop growth and survival, increasing rotation length, decreasing product quality, hindering tending and impeding stand access (Nelson *et al.*, 1985; Busby, 1988; Richardson, 1989; McCracken, 1995; Walter *et al.*, 1995).

Early weed control in *Pinus radiata* will result in maximum growth response (Adams and Dutkowski, 1995). Conversely, if competing vegetation is not controlled in the critical one to three year period, stem diameter reductions will be proportional to the number of years without vegetation control (Wagner *et al.*, 1995). Maximum crop production invariably occurs in the absence of competing weeds (Cousens *et al.*, 1987 *ex* Radosevich and Knowe, 1992). Weed control is the single most important treatment to improve tree growth (Richardson, 1992). Generally, weeding is not required after canopy closure (Nambiar, 1989). Therefore vegetation management should be designed to accelerate initial tree growth, especially during the first few years after establishment.

Manual release, i.e. hoeing, slashing and hand pulling of weeds, were the 'standard' method of weed control in the south western Cape (Donald, 1986; South *et al.*, 1992). Gous (1995) found that chemical weed management was significantly better than manual weed management in *P. radiata* plantations in the southern Cape.

Wages in the southern and western Cape increased from R1.00/unit in 1970 to R15.00/unit in 1986 (Donald, 1986). In 1995 the cost of labour is R80.00 (R40.00 per man day for wages and R40.00 for direct overheads) per unit per day (C. Bekker, pers. comm., 1995). This increase in labour costs is a strong incentive to search for a more cost effective alternative to manual weed control (Barthod, 1995; Gous *et al.*, 1992; Lyle, 1981), for example with herbicides that have some residual or post-emergent effect, resulting in longer relief from weeds.

5.2 Materials and methods

The trial was conducted on an almost marginal site in the southern Cape near Knysna on the timber farm, Dubbelberg. The trial area has Hutton and Glenrosa soil forms (Soil Classification Working Group, 1991), a 15-20^0 slope and a mean annual rainfall of 750 mm. According to the Köppen formula the site has hot summers, mild winters and all months are moist (Koeppe and De Long, 1958). The site has a predicted mean annual increment (m.a.i.) of 10 m^3/ha (L. Viljoen, pers. comm., 1994).

A visual assessment of weed cover was carried out before weed control treatments. Two subsequent assessments were conducted 12 and 22 months later to determine the effect of vegetation management on weed cover.

Glyphosate was used as a knockdown herbicide in two formulations, i.e. a 360g a.i./litre (ROUNDUP), and a 180g a.i./litre (STING) formulation. The 180g a.i./litre glyphosate formulation was used in conjunction with two pre-emergent herbicides, thiazopyr and acetochlor, for each of the glyphosate rates to determine if longer relief from weeds would occur. Table 5.1 displays the treatments tested on indigenous herbaceous shrubs (macchia/fynbos) in a one year old virgin *P. radiata* stand. A mechanical ring weeding of one metre radius was included as a control treatment. Herbicides were applied in a strip (1.5m wide) over-the-top of uncovered one year old *P. radiata*, established in an ex-macchia community, as this is the most economical and practical way of applying herbicides (Nelson *et al.*, 1985). The weather during spraying (September 1992) was cool (approximately 16°C) with no wind.

Table 5.1: Herbicides applied, active ingredients and herbicide cost/ha

Knockdown Herbicide *Trade Name#*	**a.i. (g/ha)**	**Pre-emergent Herbicide** TRADE NAME*	**a.i. (g/ha)**	**Herbicide cost/ha June '95**
Glyphosate ***Roundup#***	720 1080 1440	- - -		R51,74 R77,61 R103,48
Glyphosate ***Sting#***	720 1080 1440	- - -		R77,52 R116,28 R155,04
Glyphosate ***Sting#***	720 1080 1440	**Thiazopyr** VISOR*	720 720 720	R932,52 R971,28 R1010,04
Glyphosate ***Sting#***	720 1080 1440	**Acetochlor** HARNESS*	2700 2700 2700	R260,61 R299,37 R338,13
Glyphosate ***Sting#***	720 1080 1440	**Thiazopyr + Acetochlor** VISOR* and HARNESS*	720 + 2700 720 + 2700 720 + 2700	R1115,61 R1154,37 R1193,13
Glyphosate ***Sting#***	720 1080 1440	**Thiazopyr + Acetochlor** VISOR* and HARNESS*	480 + 1800 480 + 1800 480 + 1800	R769,58 R808,34 R847,10
Control				R240,00

The trial area was burnt six months prior to planting. Espacement of trees in the trial area was 3m x 3m, with 1111 stems/ha at time of planting. Blanking was carried out 3 months after initial planting. The experiment was established as a randomized complete block with three blocks. Each block contained nineteen treatments totalling 57 plots in the experiment. Table 5.1 displays herbicide particulars and the herbicide cost per totally sprayed hectare. However, the herbicide cost listed in Table 5.1, should be halved as only half of the area per hectare is sprayed because of the strip spraying. Herbicides were diluted with clean water and applied by knapsack sprayers with a standard "TK2"-brass nozzle, at 300ℓ solution per hectare. Single row plots were used with eight healthy trees per plot. A 1.5m buffer was used between the treatments.

Tree heights were measured with a measuring rod to the nearest cm and diameters 10cm above ground level (D_{10}) with an electronic calliper, to the nearest 0.1mm. The first measurements were taken immediately before the initial treatments were applied. Four subsequent measurements were carried out at six month intervals after application.

A one-way analysis of variance was carried out with 12 and 22 month height and diameter increments as response variables. Interactions between knockdown and pre-emergent herbicides were tested for their statistical significance. An analysis of this two-factor trial with glyphosate (180g a.i./litre formulation) as first and pre-emergents as second factor was carried out. An analysis of variance was calculated with 12 month height increment as response variable, within each rate of the 180g a.i./litre formulation of glyphosate, to test the difference between pre-emergent herbicides. The linearity of the responses were tested within both formulations of glyphosate. In case of non-significance of the two factor interaction, the main effects were tested for their significance.

5.3 Results

The dominant vegetation families were the Thymelaeaceae, Restionaceae, Proteaceae and the Leguminosae. These plants were controlled effectively by glyphosate at the three rates tested. Visual assessments indicated that herbicide treatments gave longer relief from weeds than the manual ring weeding control. Twenty two months after application, weeds treated with the glyphosate-acetochlor mixture clearly had less regrowth than weeds treated with any of the other pre-emergent treatments.

For height at the age of 12 and 22 months after application and diameter at 22 months after application, the hypothesis of equal treatment means was rejected at the 0.05 level of significance, indicating that at least one of the treatment means differed from the others.

Figure 5.1 shows the mean diameter increment for the 360g a.i./litre formulation glyphosate, compared to the 180g a.i./litre formulation of glyphosate. Figure 5.2 displays the mean height increment for the 360g a.i./litre formulation glyphosate, compared to the 180g a.i./litre formulation of glyphosate. One year after treatment application, the control had the most positive significant effect on height increment. Twenty two months after application, the 720g a.i. glyphosate, in the 360g a.i./litre formulation, performed best in terms of height and diameter increments.

The model with height as dependent variable revealed significant interactions between knockdown and pre-emergent herbicides, 12 months after application. Statistical analysis disclosed that within the lower rate of glyphosate, the thiazopyr-acetochlor mixture (each at 2ℓ/ha) was significantly better than the other pre-emergents (Table 5.2). With regard to the effect of application rates, the lowest glyphosate rates (720g a.i./ha), yielded a positive statistically significant effect on diameter and height growth (Figure 5.3 and Figure 5.4). Therefore, a negative linear response was found within glyphosate rates.

The analyses of height and diameter increment data revealed no significant difference within the pre-emergent herbicides added to glyphosate. However, a visual assessment of weed regrowth revealed that the glyphosate-acetochlor mixture gave the longest control of weeds.

Table 5.2: Means for one year height increment of pre-emergent treatments within the 720g a.i./ha rate of glyphosate

Pre-emergent herbicide grouping	Mean height increment (cm)	
No Pre-emergents	66.1	a
2ℓ Thiazopyr & 2ℓ acetochlor	60.6	a
3ℓ Thiazopyr & 3ℓ acetochlor	56.1	b
3ℓ Thiazopyr	54.2	b
3ℓ Acetochlor	53.4	b

Based on Duncan's Multiple Range Test, means not sharing a common letter differ significantly (P = 0.05).

Standard error of the mean = 1.04cm

Standard error of the difference between two means = 1.47cm

Table 5.3: Herbicides applied, cost/ha sprayed, including application cost and estimated volume required for financial break-even above manual weeding

Knockdown and pre-emergent herbicide applied per ha	a.i. (g/ha)	Treatment cost per ha (R) July '95	Tmt. no.	Break-even volume increase (m^3/ha)
Glyphosate Roundup#	720	R145.87	1	-2.73
Glyphosate Roundup#	1080	R158.81	2	-2.36
Glyphosate Roundup#	1440	R171.74	3	-1.98
Glyphosate Sting#	720	R158.76	4	-2.36
Glyphosate Sting#	1080	R178.14	5	-1.80
Glyphosate Sting#	1440	R197.52	6	-1.23
Glyphosate Thiazopyr	720 720	R586.26	7	10.05
Glyphosate Thiazopyr	1080 720	R605.64	8	10.62
Glyphosate Thiazopyr	1440 720	R625.02	9	11.18
Glyphosate Acetochlor	720 2700	R250.31	10	0.30
Glyphosate Acetochlor	1080 2700	R269.69	11	0.86
Glyphosate Acetochlor	1440 2700	R289.07	12	1.42
Glyphosate Thiazopyr Acetochlor	720 720 2700	R677.81	13	12.71
Glyphosate Thiazopyr Acetochlor	1080 720 2700	R697.19	14	13.28
Glyphosate Thiazopyr Acetochlor	1440 720 2700	R716.57	15	13.84
Glyphosate Thiazopyr Acetochlor	720 480 1800	R504.79	16	7.69
Glyphosate Thiazopyr Acetochlor	1080 480 1800	R524.17	17	8.25
Glyphosate Thiazopyr Acetochlor	1440 480 1800	R543.55	18	8.81
Ring weeding control		R240.00	19	

5.4 Discussion

Floristic surveys indicated that weeds treated with herbicides took longer to recover than manually controlled weeds. Gous (1995) found that chemical weed management was significantly better than manual weed management in southern Cape *P. radiata* plantations. Zwolinski *et al.* (1995) working in fynbos, concluded that chemical weed control produced improved height, ground line diameter, and volume in *P. radiata* compared to manually controlled weeds. Manually released trees would have to be released again within two years because of excessive weed regrowth (M. Bekker, pers. comm., 1994). Three years after application the chemically controlled weeds did not require another treatment (R. Van Zyl pers. comm., 1995). This will increase the cost of manual treatments and will most certainly affect the choice of weed management treatment. The visual assessment indicated that the glyphosate-acetochlor mixture gave longer control of weeds than the other glyphosate-pre-emergent treatments. Unfortunately this trait did not show in the height and diameter responses.

It is not recommended to apply glyphosate over-the-top of *P. radiata* as it caused severe die-back of growing tips. Therefore, the visual trait mentioned above could not be detected by the statistical analysis. The trees took almost two years to recover, to their former height, from the herbicide damage.

Figures in Table 5.3 are based on a m.a.i. of 10 m^3/ha (L. Viljoen, pers. comm., 1994) at age 20; labour cost of R80.00 per man day (C. Bekker, pers. comm., 1995); current (June 1995) weighted average timber price of R78.79/m^3, a real discount rate of 3% and a total volume of 269 m^3/ha at clearfelling, age 30 years. The costs above R240.00/ha, i.e. the cost of mechanical weeding, were calculated with compound interest (R = 3%) between treatment age and clearfelling.

Formula used for calculations in Table 5.3:

$$\text{Break-even volume} = \frac{\text{Compounded value at clearfelling}}{\text{Weighted average timber price per m}^3}$$

where $R \times 1.03^n$ = Compounded value at clearfelling

R = cost above R240.00, n= clear felling age - treatment age

(H.J.E. Uys, pers. comm., 1994.)

As manually controlled plots needed another release two years after the first ring weeding (costing R240.00/ha), chemical weed management proved an even better financial option than revealed by Table 5.3. Less volume of timber would therefore be required for financial break-even, if another manual weeding is required.

Glyphosate required less volume of timber than the glyphosate pre-emergent mixtures for financial break-even (Table 5.3). However, glyphosate caused die-back damage to *P. radiata* growing tips when applied over-the-top. Gous (1995) found the same results in *P. radiata* with similar weeds. It is therefore recommended that young tips of the trees should be avoided when applying glyphosate.

The addition of pre-emergent herbicides to glyphosate showed no significant improvement to *P. radiata* height and diameter growth. However, the addition of 3ℓ/ha acetochlor to glyphosate at the highest rate (1440g a.i./ha) only required 1.42m^3 of additional timber for financial break-even. This mixture should be further investigated in fynbos, as it gave a longer relief from weeds than glyphosate or the other glyphosate pre-emergent mixtures.

Macchia vegetation has strong vegetative growth potential, provided roots are not damaged. The herbicides used in this investigation are systemic and killed macchia root systems. Manual weeding virtually leaves the roots unharmed. Therefore, chemical weed management gave longer control of weeds than manual weeding (Gous, 1995).

5.5 Conclusions

Chemical weed management gave longer relief from weeds than manual weed management. Glyphosate caused die-back damage to *P. radiata* growing tips when applied over-the-top and therefore this method of application should be avoided. The addition of pre-emergents to the knockdown herbicide gave a longer relief from weeds than only applying glyphosate. These mixtures should be investigated further.

Acetochlor gave longer relief from weeds than thiazopyr in fynbos vegetation. Little or no difference was visible between the glyphosate-acetochlor mixture and glyphosate-acetochlor-thiazopyr mixture. Thiazopyr is mainly a grass pre-emergent and therefore it is not surprising that an attempt to control fynbos with it, had little or no beneficial effect on *P. radiata*. It would be advisable to test the product in grass infested areas.

The addition of pre-emergents, especially acetochlor at 3ℓ/ha, to glyphosate prolongs the control of a wide range of fynbos species, particularly the Thymelaeceae and the Restionaceae.

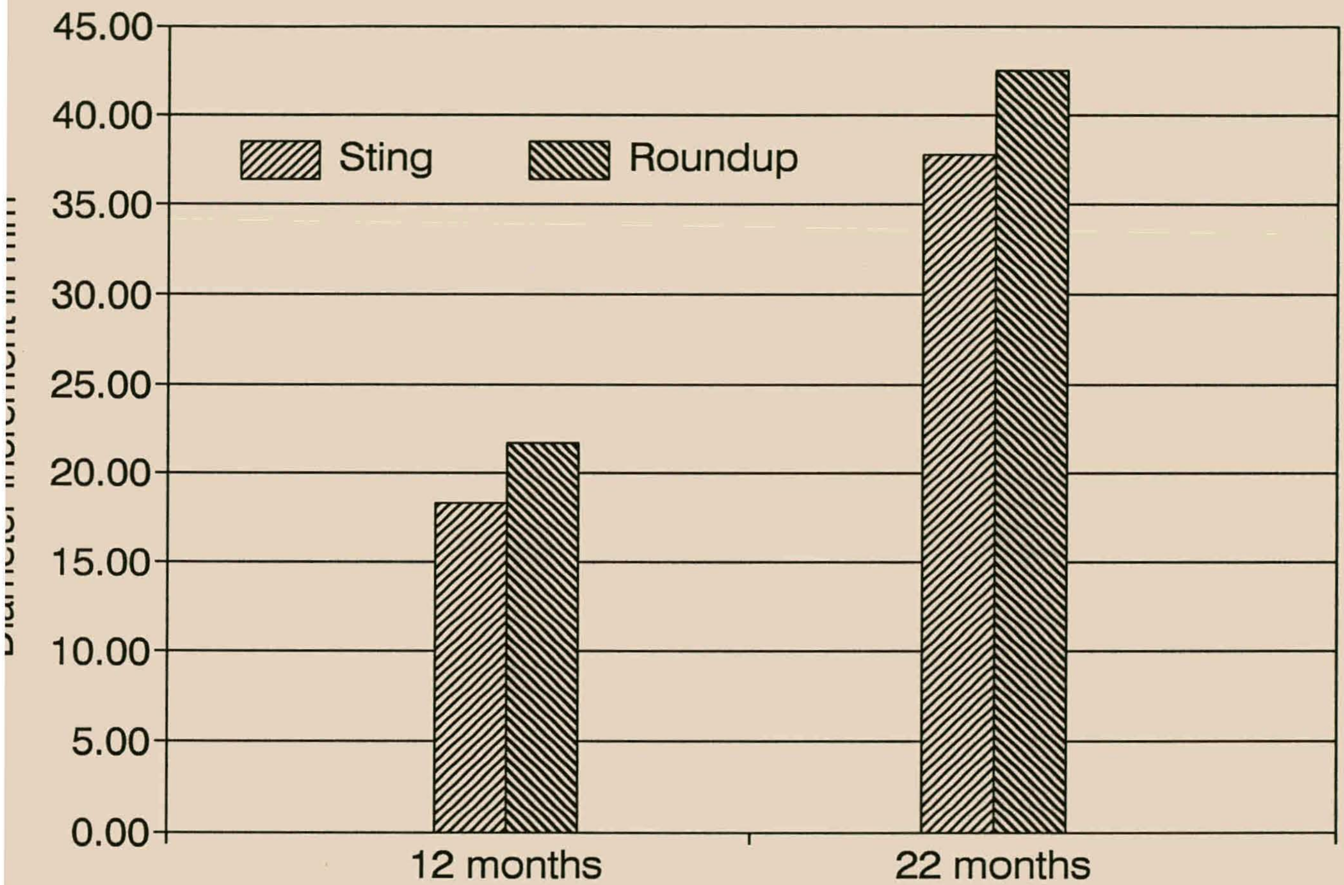

Figure 5.1: The mean effects of three levels of Sting and Roundup application on diameter increment of P. radiata 12 and 22 months after application

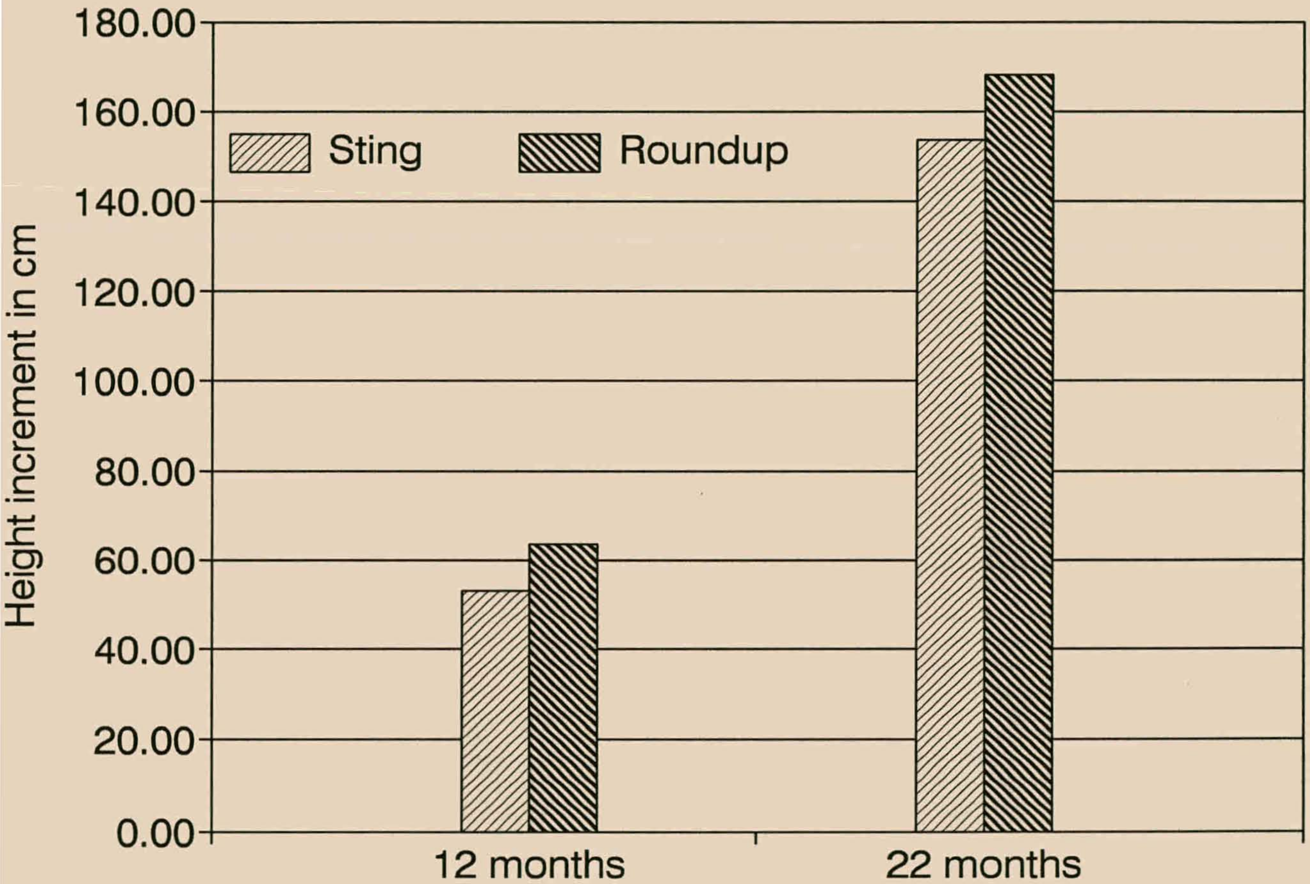

Figure 5.2: The mean effects of three levels of Sting and Roundup applications on height increment of P.radiata 12 and 22 months after application

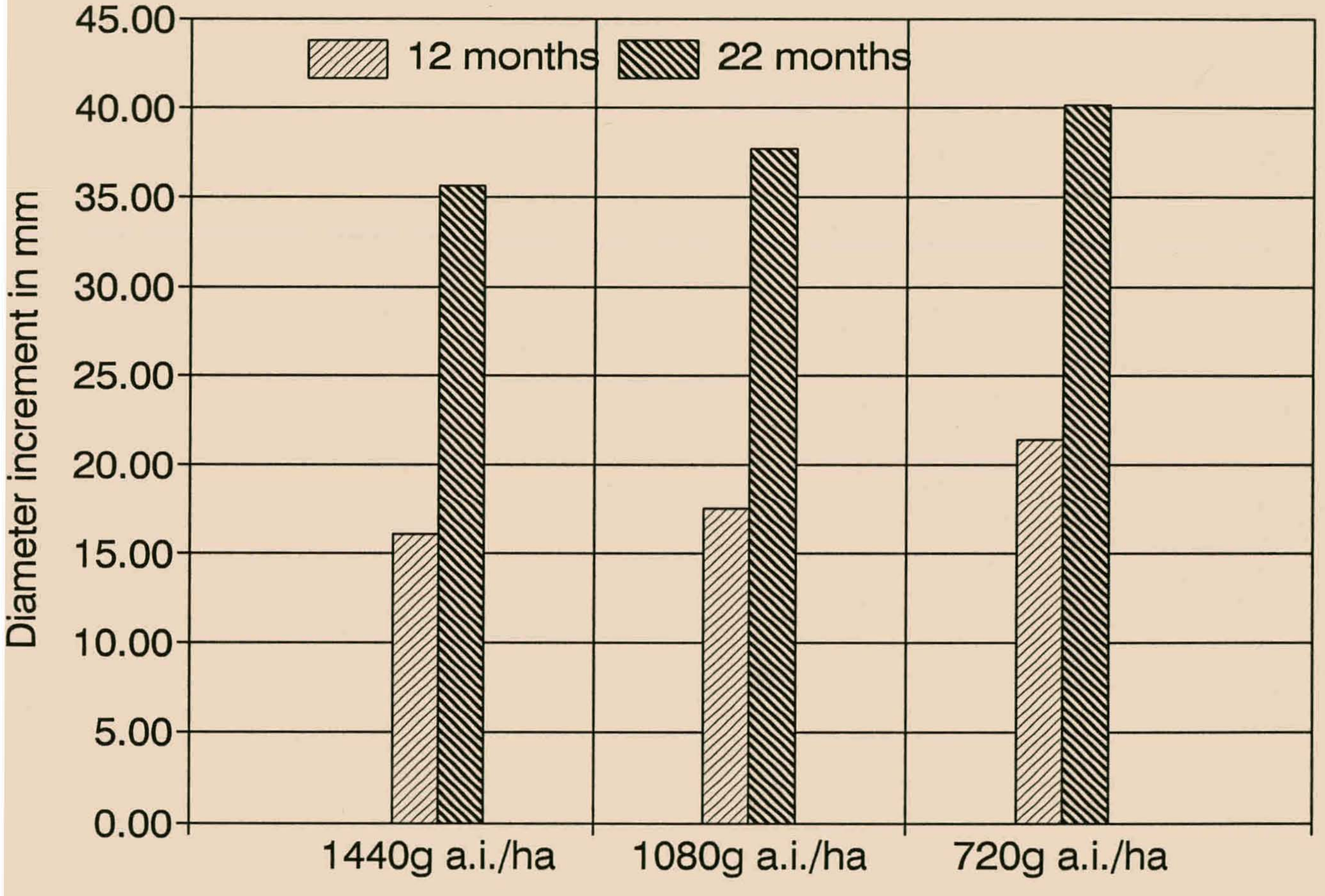

Figure 5.3: Diameter growth differences of P. radiata at 12 and 22 months after treatment with three rates of Sting

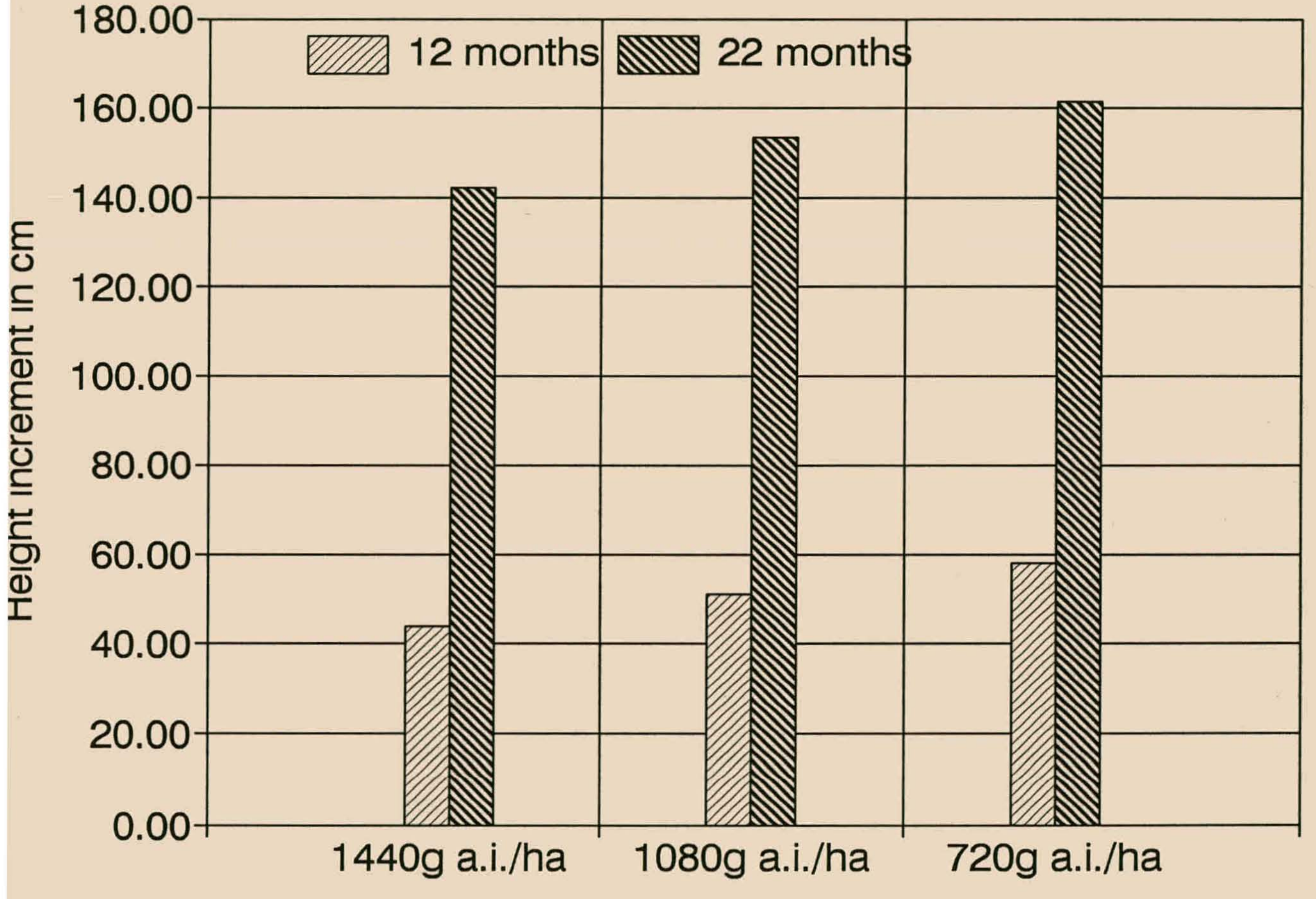

Figure 5.4: Height growth differences of P. radiata at 12 and 22 months after treatment with three rates of Sting

6. Summarized conclusions

In this study, chemical vegetation management was less expensive and provided a longer relief from competing vegetation than manual weeding, except in the Delheim hexazinone experiment where inadequate active ingredient (a.i.) was applied. No significant differences occurred between manual ring weeding and total manual weeding. Therefore, when chemical vegetation management cannot be practised, manual ring weeding should be used, because it is less expensive and environmentally more acceptable.

Hexazinone and glyphosate were the most successful herbicides to control vegetation in *Pinus radiata* plantations. Diameter and height growth of *P. radiata* were significantly improved by glyphosate at 1500g a.i./ha (shielded application) and hexazinone at 2000g a.i./ha. Glyphosate and hexazinone significantly reduced plant moisture stress (p.m.s.) of *P. radiata*, by suppressing weed growth.

Hexazinone at 2000g a.i./ha applied over-the-top to *P. radiata* caused no damage to the trees. A 1.5m strip spray over *P. radiata* (with hexazinone) is recommended, as there were no significant differences between strip and total area sprayed. Hexazinone liquid significantly out-performed the powder formulation in diameter growth. Hexazinone treatment of *P. radiata* plantations can be recommended for aerial application.

Glyphosate caused die-back of *P. radiata* growing tips. Therefore, over-the-top application is not recommended. Application of glyphosate at 1500g a.i./ha is recommended, if trees are protected or avoided. The addition of pre-emergents (thiazopyr and acetochlor) to glyphosate gave a longer relief from weeds than only applying glyphosate.

Vegetation control in summer was significantly better than vegetation control in the other three seasons.

It is recommended that the trials should be assessed again to determine the residual herbicide effects and the long-term tree growth response to the different weeding treatments.

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8. Appendixes

Appendix 2.1: Floristic survey of Delheim Hexazinone experiment 1989 - 1991

Species	1989		1990		1991	
	rank	% cover	rank	% cover	rank	% cover
Metalasia muricata	1	18.21	3	10.12	8	3.64
UNCOVERED AREA	2	16.20	1	28.14	2	16.03
Hypochoeris radicata	3	6.70	2	14.70	1	17.03
Chrysanthemoides monolifera	4	5.02	16	1.21	14	2.18
Rumex acetocella	5	3.88	8	2.71	22	0.73
Helichrysum riveum	6	3.78	31	0.41	12	2.35
Helichrysum crispum	7	3.33	4	4.91	3	11.59
Pelargonium chamaedryfolium	8	3.26	15	1.23	15	1.34
Helichrysum hebelepis	9	2.82	44	0.24	61	0.03
Briza minima	10	2.74	27	0.49	16	1.34
Hermania filifolia var *grandicalyx*	11	2.47	34	0.34	32	0.45
Atanasia trifurcata	12	2.21	9	2.63	13	2.23
Helichrysum revolutum	13	2.04	13	2.01	30	0.52
Salvia chamelaegnea	14	1.88	21	0.67	20	0.75
Eriocephalus africanus	15	1.83	50	0.20	51	0.10
Osteospermum sinuatum	16	1.78	22	0.67	39	0.24
Oftia africana	17	1.77	26	0.54	31	0.48
Inula	18	1.56	18	0.74	36	0.29
Stoebe africana	19	1.37	12	2.43	4	5.70
Protasparagus africanus	20	1.23	19	0.69	34	0.36
Silene	21	0.96	53	0.14	28	0.56
Chrysoma oblongifolia	22	0.95	61	0.01	56	0.06
Aspalathus galiodes	23	0.93	25	0.56	21	0.75
Aspalathus ciliaris	24	0.91	59	0.07	58	0.05
Pentaschistis aspera	25	0.81	10	2.56	6	4.04
Diospyros glabra	26	0.70	24	0.56	17	0.95
Vicia faba	27	0.69	47	0.20	25	0.63
Thesium	28	0.65	42	0.26	50	0.11
Fecinia	29	0.58	37	0.32	24	0.64
Cynodon dactylon	30	0.56	7	2.80	10	2.85
Briza maxima	31	0.53	11	2.45	5	5.05
Acacia mearnsii	32	0.52	54	0.13	48	0.13
Anthospermum aetiopicum	33	0.51	38	0.32	46	0.13
Digitaria eriantha	34	0.49	30	0.44	11	2.40
Pinus radiata	35	0.48	14	1.35	7	4.02
Rhus angustifolia	36	0.48	23	0.63	27	0.56
Dianthus caespitosus caespitosus	37	0.45	52	0.15	45	0.14
Podalyria glauca	38	0.41	43	0.25	53	0.07
Sonchus	39	0.39	17	0.74	23	0.72
Lactuca	40	0.37	33	0.35	40	0.23
Rubus spp.	41	0.35	28	0.49	29	0.53
Pelargonium alternans	42	0.31	58	0.07	54	0.06
Senicio rigidus	43	0.27	35	0.33	49	0.11
Salvia lanceolata	44	0.25	60	0.04	55	0.06
Atriplex semibaccata	45	0.24	51	0.17	60	0.03
Olea africana	46	0.23	32	0.40	33	0.43
Cyanella hyacinthoides	47	0.22	40	0.28	35	0.31
Acacia melanoxylon	48	0.20	48	0.21	37	0.29
Antholyza plicata	49	0.20	56	0.12	59	0.04
Paspalium dilatatum	50	0.18	20	0.68	26	0.58
Leonotis leonurus	51	0.17	46	0.21	42	0.18
Maytenum oleiodes	52	0.16	41	0.27	43	0.16
Helichrysum asperum	53	0.14	63	0.00	62	0.02
Ehrharta capensis	54	0.13	6	2.80	9	3.17
Themeda triandra	55	0.09	29	0.47	19	0.82
Oxalis pescapre	56	0.08	5	2.83	18	0.85
Cliffortia ruscifolia	57	0.07	36	0.33	52	0.08
Homeria	58	0.07	45	0.23	47	0.13
Helichrysum fotidium	59	0.07	49	0.21	38	0.26
Mariscus thunbergii	60	0.06	39	0.31	44	0.16
Cliffortia robusta	61	0.05	62	0.01	63	0.01
Lolium loliaceum	62	0.04	55	0.12	41	0.22
Plumbago tristis	63	0.04	57	0.09	57	0.06

Appendix 2.2: Mean plant moisture stress (kPa) for Delheim Hexazinone experiment during summer 1990

TREATMENTS	17/01 1990	16/02 1990	02/03 1990	16/03 1990	30/03 1990
Total manual weeding	0.85	0.70	0.77	0.99	0.78
Total manual weeding	1.12	0.80	0.81	1.15	0.81
Total manual weeding	0.73	0.90	0.93	0.93	0.64
Total manual weeding	0.87	0.90	0.97	0.70	0.87
Total manual weeding	0.68	1.04	1.08	1.00	0.80
Velpar 1,5kg/ha total	0.82	0.90	0.92	0.84	0.83
Velpar 1,5kg/ha total	0.82	0.74	0.75	0.95	0.78
Velpar 1,5kg/ha total	0.78	0.80	0.85	1.02	0.89
Velpar 1,5kg/ha total	0.68	1.30	1.32	0.92	0.66
Velpar 1,5kg/ha total	1.01	0.80	0.85	0.93	1.00
Velpar 1,5kg/ha strip	0.91	0.90	0.98	0.90	0.87
Velpar 1,5kg/ha strip	1.20	1.00	1.02	1.13	0.96
Velpar 1,5kg/ha strip	0.78	1.02	1.04	0.99	0.92
Velpar 1,5kg/ha strip	0.68	1.10	1.14	1.20	0.71
Velpar 1,5kg/ha strip	0.98	1.02	1.09	1.20	0.89
Velpar 1,0kg/ha total	0.95	1.04	1.04	0.95	0.84
Velpar 1,0kg/ha total	0.81	0.91	0.96	1.15	0.65
Velpar 1,0kg/ha total	0.82	0.90	0.91	0.95	1.02
Velpar 1,0kg/ha total	0.97	1.14	1.18	1.05	0.87
Velpar 1,0kg/ha total	1.07	1.20	1.27	1.30	0.82
Velpar 1,0kg/ha strip	0.84	1.13	1.13	0.90	0.91
Velpar 1,0kg/ha strip	1.06	1.03	1.03	1.09	0.84
Velpar 1,0kg/ha strip	0.77	1.20	1.20	1.20	0.89
Velpar 1,0kg/ha strip	0.80	1.09	1.09	0.89	0.83
Velpar 1,0kg/ha strip	1.16	1.15	1.18	1.02	1.06
Velpar 6,0 l/ha total	0.76	0.75	0.75	0.83	0.80
Velpar 6,0 l/ha total	0.75	0.74	0.79	0.88	0.71
Velpar 6,0 l/ha total	0.84	0.60	0.64	0.80	0.80
Velpar 6,0 l/ha total	0.79	0.72	0.78	0.83	0.92
Velpar 6,0 l/ha total	0.66	0.80	0.91	0.83	0.78
Velpar 6,0 l/ha strip	0.91	0.91	0.91	1.02	0.92
Velpar 6,0 l/ha strip	1.06	0.80	0.88	1.10	0.86
Velpar 6,0 l/ha strip	0.83	0.91	0.91	0.89	0.93
Velpar 6,0 l/ha strip	0.97	0.68	0.68	0.80	0.88
Velpar 6,0 l/ha strip	0.78	1.02	1.02	0.90	0.99
Velpar 4,0 l/ha total	1.20	1.03	1.02	0.94	0.90
Velpar 4,0 l/ha total	0.88	1.04	1.04	1.02	0.93
Velpar 4,0 l/ha total	0.70	0.80	0.88	1.20	0.90
Velpar 4,0 l/ha total	1.30	1.30	1.22	0.95	0.98
Velpar 4,0 l/ha total	0.90	0.91	0.91	1.32	0.77
Velpar 4,0 l/ha strip	0.96	1.20	1.11	0.83	0.96
Velpar 4,0 l/ha strip	1.15	1.09	1.09	0.95	0.99
Velpar 4,0 l/ha strip	1.45	1.00	0.99	0.97	0.88
Velpar 4,0 l/ha strip	0.95	1.30	1.31	0.94	0.97
Velpar 4,0 l/ha strip	0.99	1.21	1.21	1.08	0.99
Ring weeding 1m radius	0.93	0.90	0.95	0.89	0.85
Ring weeding 1m radius	1.03	0.80	0.82	1.12	0.75
Ring weeding 1m radius	1.00	0.89	0.80	1.14	0.78
Ring weeding 1m radius	0.87	1.10	1.16	0.87	0.88
Ring weeding 1m radius	0.83	1.10	1.00	1.12	0.99

Appendix 3.1: Floristic survey of five herbicide experiment, Delheim 1990 - 1991, percentage cover of weeds

Species	Average for all treatments				Mean values for all rates %				
	1990 *rank*	1990 %	1991 *rank*	1991 %	Velpar	Roundup	Frepar	Arsenal	R & A
Metalasia muricata	1	10.11	4	4.36	0.84	0.43	9.89	5.86	4.8
Uncovered area	2	9.88	1	31.40	37.75	42.57	19.5	26.86	30.31
Chrysanthemoides monolifera	3	6.64	9	2.75	0.91	1.14	7.9	2.7	1.11
Helichrysum cripum	4	5.55	10	2.26	0.98	1.45	3.12	3.8	1.93
Stoebe incana	5	5.54	8	2.87	1.65	1.4	3.85	4.23	3.23
Helichrysum riveum	6	3.63	12	1.50	1.12	0.94	1.85	2.14	1.47
Hypochoeris radicata	7	2.96	2	10.54	7.03	6.15	15.92	10.34	13.27
Protasparagus aethiopicus	8	2.79	27	0.68	0.21	0.12	1.23	0.85	1.01
Athanasia parviflora	9	2.74	21	0.95	0.12	0.1	1.59	1.68	1.27
Oftia africana	10	2.63	28	0.60	0.16	0.19	1.16	0.92	0.59
Helichrysum revolutum	11	2.54	18	1.05	0.60	0.65	1.36	1.69	0.97
Pinus radiata	12	2.40	3	5.03	4.98	5.49	4.71	4.49	5.49
Atanasia trifurcata	13	2.35	16	1.23	0.17	0.09	2.1	1.79	2.01
Rumex acetacella	14	2.17	39	0.39	0.03	0	0.85	0.82	0.27
Pelargonium chamaedryfolium	15	2.15	22	0.88	0.09	0.04	0.95	1.95	1.38
Senicio spp.	16	2.07	52	0.19	0.02	0.03	0.23	0.66	0.02
Hermannia rudis	17	1.97	25	0.84	0.07	0.04	1.7	1.5	0.91
Briza minima	18	1.95	13	1.46	1.96	2.13	0.96	1.22	1.02
Salvia chamelaegnea	19	1.94	42	0.35	0.01	0.02	0.62	0.82	0.27
Stoebe africana	20	1.87	6	3.78	2.42	2.97	4.07	6.38	3.07
Aspalathus ciliaris	21	1.79	23	0.87	0.20	0.25	1.91	1.25	0.73
Eriocephalus africanus	22	1.43	64	0.05	0.06	0.04	0.08	0.05	0.04
Aspalathus galiodes	23	1.42	20	0.96	0.48	0.62	1.08	1.33	1.31
Protasparagus africanus	24	1.23	47	0.25	0.03	0.03	0.02	0.82	0.36
Anthospermum aetiopicum	25	1.23	24	0.86	0.48	0.77	1.17	0.8	1.1
Briza maxima	26	1.13	14	1.30	2.32	2.93	0.54	0.21	0.52
Euryops abrotanifolius	27	1.04	72	0.01	0	0	0.01	0.02	0
Themeda triandra	28	0.97	17	1.09	2.05	1.62	0.64	0.46	0.67
Osteospermum sinuatum	29	0.95	56	0.18	0.08	0.1	0.07	0.56	0.1
Silene	30	0.90	55	0.18	0.21	0.04	0.13	0.45	0.05
Inula	31	0.87	29	0.57	0.79	0.47	0.48	0.43	0.69
Digitaria eriantha	32	0.79	30	0.56	0.87	1.16	0.1	0.21	0.48
Cynodon dactylon	33	0.75	11	1.64	3.15	2.63	0.34	0.65	1.45
Ursinia paleacea	34	0.74	73	0.01	0.01	0	0	0.01	0.01
Pentzia incana	35	0.68	49	0.24	0.20	0.2	0.11	0.37	0.34
Diospyros glabra	36	0.65	48	0.25	0.04	0.17	0.48	0.24	0.34
Senicio rigidus	37	0.63	54	0.18	0.05	0.02	0.08	0.42	0.33
Protasparagus rubicundus	38	0.63	45	0.26	0.13	0.08	0.05	0.65	0.4
Pentaschistis aspera	39	0.62	7	3.56	5.26	5.71	1.23	1.43	4.19
Berkheye cuneata	40	0.60	51	0.21	0.13	0.14	0.1	0.43	0.26
Rubus spp.	41	0.55	34	0.45	0.28	0.15	0.8	0.8	0.2
Rhus angustifolia	42	0.52	26	0.73	0.40	0.63	1.33	0.73	0.54
Salvia lanceolata	43	0.48	59	0.10	0.02	0	0.05	0.1	0.33
Selago serrata	44	0.43	50	0.21	0.17	0.12	0.47	0.13	0.17
Lactuca	45	0.43	31	0.53	0.52	0.76	0.27	0.4	0.68
Tephrosia capensis	46	0.42	63	0.06	0.07	0.12	0.06	0.05	0.02
Leucospermum truncatulum	47	0.42	38	0.4	0.02	0.21	0.73	0.51	0.55
Thesium carinatum	48	0.41	68	0.02	0.00	0.08	0.01	0.01	0
Podalyria calyptrata	49	0.40	62	0.07	0.04	0.01	0.02	0.14	0.13
Olea africana	50	0.33	35	0.43	0.17	0.12	0.7	0.96	0.19
Helichrysum hebelepis	51	0.23	60	0.09	0.16	0.12	0	0.07	0.12
Maytenus oleoides	52	0.21	43	0.34	0.18	0.07	0.8	0.4	0.23
Homeria pallida	54	0.20	36	0.42	0.06	0.17	0.76	0.69	0.42
Helichrysum asperum	53	0.20	65	0.04	0.01	0.01	0.04	0.05	0.07
Helichrysum foetidum	55	0.19	15	1.26	0.84	0.65	2.31	1.99	0.53
Sonchus	56	0.16	41	0.37	0.20	0.32	0.42	0.49	0.44
Cyanella hyacinthoides	57	0.15	58	0.12	0.01	0.01	0.3	0.2	0.08
Pelargonium cucullatum	58	0.15	32	0.47	0.48	0.13	0.5	0.52	0.74
Acacia mearnsii	60	0.14	53	0.19	0.07	0.08	0.25	0.45	0.11
Cliffortia ruscifolia	59	0.14	57	0.14	0.19	0.09	0.1	0.2	0.14
Bobartia filiformis	61	0.11	61	0.09	0.01	0.06	0.1	0.23	0.06
Erharta bulosa	62	0.11	5	4.20	7.37	9.26	0.93	1.05	2.41
Leonotis leonurus	63	0.10	67	0.02	0.05	0	0.01	0.03	0.03
Paspalium dilatatum	64	0.09	33	0.45	0.76	0.77	0.19	0.15	0.4
Acacia melanoxylon	65	0.08	46	0.25	0.00	0.21	0.56	0.25	0.25
Indigofera heterophylla	66	0.08	76	0	0	0	0	0	0.01
Oxalis dentata	67	0.07	40	0.38	0.47	0.61	0.27	0.12	0.45
Gladiolus permeabilis	68	0.06	66	0.02	0	0.03	0	0.01	0.04
Lolium loliaceum	69	0.05	37	0.40	0.68	1.06	0.1	0.05	0.13
Mariscus thunbergii	70	0.04	74	0.01	0	0.02	0.01	0	0
Felicia muricata	71	0.03	75	0.01	0.02	0	0	0.01	0
Ehrharta capensis	73	0.03	19	1.03	1.99	2.29	0.41	0.3	0.18
Pelargonium alternans	72	0.03	44	0.33	0.43	0	0.36	0.4	0.45
Commelina africana	76	0.01	69	0.01	0	0	0	0.03	0
Rhus crenata	75	0.01	70	0.01	0.01	0	0	0	0.02
Solanum supinum	74	0.01	71	0.01	0	0	0.03	0.01	0

107 Species were identified. The percentage cover of the 33 species not listed were negligible.